2013

Development of Methods and Specifications for the Use of Inertial Profilers and the International Roughness Index for Newly Constructed Pavement

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JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

JTRP

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SPR-3300
Report Number: FHWA/IN/JTRP-2013/09
DOI: 10.5703/1288284315211

RECOMMENDED CITATION

Harris, D. *Development of Methods and Specifications for the Use of Inertial Profilers and the International Roughness Index for Newly Constructed Pavement*. Publication FHWA/IN/JTRP-2013/09 Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2013. doi: 10.5703/1288284315211.

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ACKNOWLEDGMENTS

This research project was sponsored by the Indiana Department of Transportation (INDOT) in cooperation with the Federal Highway Administration through the Joint Transportation Research Program (JTRP). The author would like to thank Brian Schleppi and Dan Radanovich of the Ohio Department of Transportation (ODOT), Terry Treutel of the Wisconsin Department of Transportation (WISDOT), Steve Karamihas of the University of Michigan, and Scott Newbolds of Benedictine College for their advice and incites regarding IRI specifications. Sincere thanks are extended to Mike Moredock, Kyle Long, Tony Johnson, Kim Lane, and Maurice Hendryx of INDOT for their assistance with the IRI equipment and field IRI testing. The author would like to acknowledge the input, comments, and help of study advisory committee (SAC) members: from INDOT; Samy Noureldin, Mark Miller, Ron Walker, and Greg Pankow; Tom Duncan (FHWA), Mike Byers (IRMCA), and Pete Capon (APAI).

JOINT TRANSPORTATION RESEARCH PROGRAM

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NOTICE

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/IN/JTRP-2013/09	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Development of Methods and Specifications for the Use of Inertial Profilers and the International Roughness Index for Newly Constructed Pavement		**5. Report Date** June 2013 **6. Performing Organization Code**
7. Author(s) Dwayne Harris		**8. Performing Organization Report No.** FHWA/IN/JTRP-2013/09
9. Performing Organization Name and Address Joint Transportation Research Program Purdue University 550 Stadium Mall Drive West Lafayette, IN 47907-2051		**10. Work Unit No.** **11. Contract or Grant No.** SPR-3300
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplementary Notes Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.		

16. Abstract

The Indiana Department of Transportation (INDOT) is currently utilizing a profilograph and the profile index for measuring smoothness assurance for newly constructed pavements. However, there are benefits to implementing a new IRI based smoothness specification utilizing road profiles measured using inertial profilers. Technological advancements have improved the quality of road profiles measured using inertial profilers; furthermore, utilizing inertial profilers allows smoothness data to be collected much more quickly and efficiently than the methodology currently utilized by INDOT. Pavement smoothness quantified using International Roughness Index (IRI) calculated using profiles provided by inertial profiles is better correlated to user response than what is currently being utilized by INDOT. Furthermore, INDOT currently utilizes IRI to monitor the pavement smoothness throughout the remaining life of the pavement. Consequently, Utilizing IRI for measuring the smoothness of newly constructed pavements allows seamless monitoring of pavement smoothness from cradle to grave. This study presents an IRI based draft smoothness specification for newly constructed pavements utilizing profiles provide by inertial profilers. The process developing a draft specification included developing pay factor tables, developing the methodology for calculating the smoothness bonus, developing methodology for locating areas of localized roughness, and developing inertial profiler certification procedures.

17. Key Words pavement smoothness, IRI, specification, inertial profiler		**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 59	**22. Price**

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

DEVELOPMENT OF METHODS AND SPECIFICATIONS FOR THE USE OF INERTIAL PROFILERS AND THE INTERNATIONAL ROUGHTNESS INDEX FOR NEWLY CONSTRUCTED PAVEMENT

Introduction

The objective stated in the proposal for this study follows: "This research will lay the foundation for INDOT's transition from California profilograph (CP)/profile index (PI) to inertial profiler (IP)/international roughness index (IRI)-based pavement construction specification for Indiana with a bonus structure that is tied to performance." Furthermore, the proposal stated:

> The main deliverable will be a performance-based smoothness specification testing for which is based on IP/IRI technology. This study will develop such a specification for use in HMA pavement construction. Additionally, the study will evaluate the benefits of developing such a specification for PCCP construction. If beneficial, this project will also develop a specification for PCCP construction. These specifications will also include adjusted pay factors that are more in line with the expected performance of the pavement.

To satisfy the study objective, and provide the stated deliverable, this study presents an IRI-based draft smoothness specification for newly constructed pavements utilizing profiles provide by IP's. The process of developing a draft specification included developing pay factor tables, developing the methodology for calculating the smoothness bonus, developing methodology for locating areas of localized roughness, and developing inertial profiler certification procedures. The specification developed in this study is tied to the long-term performance of the pavement, because the draft specification pay factor table utilized for calculating smoothness bonus is tied directly to IRI models derived from INDOT PMS data and life cycle cost analysis (LCCA). The LCCA software utilized was developed for INDOT and the model parameters used were within INDOT normal parameters.

Benefits

One of the main benefits of IP/IRI specifications for smoothness is increased speed of data collection and processing, and improvements in performance of roughness index. Inertial profilers are much faster than profilographs for testing smoothness. This increase in testing speed will allow construction to be completed more quickly, thus saving costs and increasing safety to workers and the traveling public. Additionally, the use of IP/IRI will allow the same pavement smoothness index to be used throughout the life of the pavement in the design, construction, and management phases. This will allow for better estimations of pavement life and thus will allow for better estimation and control of costs for future maintenance, rehabilitation, and construction activities. Furthermore, the FHWA will require IRI information as part of MAP-21.

Utilizing the proposed specification ensures smoothness bonuses will be paid based on measurements tied more closely to what the INDOT customer actually feels while on INDOT's roads. The California profilograph does not provide a true profile of the road; furthermore, smoothness measurements provided by profile index based off of the California profilograph have poor correlation to user response. In comparison, the proposed specification utilizes inertial profilers to provide a "true" measurement of the road profile, and the smoothness index IRI utilizes a quarter car model to simulate user response.

The fact that the pay factor table is tied to the long-term performance of pavement is another benefit of utilizing the proposed draft specification. The draft specification pay factor table utilized for calculating smoothness bonus is tied directly to IRI models derived from INDOT PMS data and life cycle cost analysis (LCCA). The LCCA software utilized was developed for INDOT and the model parameters used were within INDOT normal parameters. The IRI model parameters are included in Table E.1 and the LCCA model parameters are included in Table E.2. The SAC decided that the proposed smoothness specifications should consist of one HMA specification and one PCC specification (April 2010 SAC meeting); consequently, the research progressed using one HMA model and one PCC model. No further research was conducted specifically on issues with thin lift HMA pavements.

Table E.3 shows the following:

- Results of the linear IRI and LCCY models used;
- The change in the ratio observed pavement life/designed pavement life for a number of initial IRI values based on the linear IRI model;
- Changes in the ratio of observed costs/designed costs for a number for the observed pavement life/designed pavement life values based on the linear LCCA model;
- Values derived from the model used to develop the pay factor tables for a number of initial IRI values.

The linear pay factor model was compartmentalized to put into a table. The pay factor table was then adjusted by increasing the 100% pay band and making the pay table symmetric about the

TABLE E.1
IRI model parameters

	AADT Start	AADT END	IRI Threshold	Design Life
HMA	250	40,000	160	20
PCC	4,000	40,000	160	30

TABLE E.2
LCCA model parameters

PCC Case 1	Life Years	Cost ($1,000)	HMA Case 3	Life Years	Cost ($1,000)
New PCC	30	$5,015	New HMA	20	$4,114
Maintenance		$82	Maintenance		$76
Functional	15	$1,620	Functional	15	$1,613
Maint		$76	Maintenance		$76
PM	8	$804	PM	15	$790
Maintenance		$76	Maintenance		$76
New HMA	20	$4,114	New HMA	20	$4,114
Maintenance		$76	Maintenance		$76
Total	73	$11,862	Total	70	$10,857
Evaluation Period (years)		40	Evaluation Period (years)		40

TABLE E.3
Results of IRI, LCCA, and Pay Factor Linear Models

Pavement Initial IRI	Linear IRI Model: Pavement Life — Observed/Designed HMA	Linear IRI Model: Pavement Life — Observed/Designed PCC	LCCA Linear Cost Model: Costs — Observed/Designed HMA	LCCA Linear Cost Model: Costs — Observed/Designed PCC	Pay Factor Table Linear Model HMA	Pay Factor Table Linear Model PCC
30	1.48	1.35	0.92	0.91	1.08	1.09
35	1.40	1.30	0.93	0.92	1.06	1.08
40	1.33	1.24	0.95	0.94	1.05	1.06
45	1.25	1.18	0.96	0.95	1.03	1.04
50	1.17	1.12	0.98	0.97	1.02	1.03
55	1.09	1.06	0.99	0.99	1.01	1.01
60	1.01	1.00	1.00	1.00	0.99	1.00
65	0.93	0.95	1.02	1.02	0.98	0.98
70	0.85	0.89	1.03	1.03	0.96	0.96
75	0.77	0.83	1.05	1.05	0.95	0.95
80	0.69	0.77	1.06	1.06	0.94	0.93
85	0.61	0.71	1.07	1.08	0.92	0.92
90	0.53	0.65	1.09	1.10	0.91	0.90

100% pay band. These changes were made in order to provide smoothness bonus results more similar to those calculated using CP/PI to allow for smoother transitioning from CP/PI to IP/IRI. These changes can be easily backed out. Utilizing the adjusted pay factor table in the proposed specification was driven by the input from the April 4, 2011, SAC meeting. The SAC expressed concerns regarding the difference in smoothness bonuses paid out using the current specification and the unadjusted IRI pay factor table (April 4, 2011, SAC meeting minutes).

Cost Benefits

The data analyzed during this study showed that the proposed specification pays out less in smoothness bonuses for rougher pavements than the current specification. In some instances, an overall disincentive would have been paid by the contractor for a few of the sections tested based on the pay factor table (see Table E-4). Therefore, a higher percentage of the money paid for smoothness bonuses would go to contractors constructing smoother pavements and contractors constructing rough pavements would be penalized.

The results of this study show that the calculated increased costs caused by constructing a pavement with increased initial IRI values to be sensitive to the model variables. Consequently, a multitude of very different pay factor tables could be generated using reasonable model inputs to the IRI models and LCCA analysis utilized. As a consequence, project specific model parameters would have to be developed and assigned to each individual project to truly analyze whether INDOT is paying too much in smoothness bonuses.

One of the cost benefits mentioned in the proposal was cost savings by having INDOT collect the inertial profiler data instead of the contractor; however, it was the opinion of the SAC that the data should be collected by the contractor in order to ensure that the data is collected in a timely manner (February 2, 2013, SAC meeting minutes).

TABLE E.4
Pay Factor Table

Midpoint IRI (in/mile)	Start IRI (in/mile)	End IRI (in/mile)	Pay Factor Model at Midpoint HMA	Pay Factor Model at Midpoint PCC	Pay Factor HMA	Pay Factor PCC
32.5	30	35	1.069	1.085	1.06	1.08
37.5	35	40	1.055	1.069	1.06	1.07
42.5	40	45	1.041	1.053	1.04	1.05
47.5	45	50	1.027	1.037	1.03	1.04
52.5	50	55	1.013	1.021	1.02	1.02
57.5	55	60	0.999	1.005	1	1.01
62.5	60	65	0.985	0.989	1	1
67.5	65	70	0.971	0.973	1	1
72.5	70	75	0.957	0.957	0.98	0.99
77.5	75	80	0.943	0.941	0.97	0.98
82.5	80	85	0.929	0.925	0.96	0.96
87.5	85	90	0.915	0.909	0.94	0.95

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GLOSSARY

Continuous IRI: The results of putting IRI filtered road profile through a moving average filter with as specified window size. For this report 25 feet was selected as the window size.
Fixed Interval IRI: The results of segmenting the IRI filtered road profile into lots of a specified length calculating the average of each lot, and then assigning the average value to each lot.
Inertial Profiler (IP): A piece of equipment utilizing an accelerometer and a laser to measure the profile of the road.
IRI: International Roughness Index a smoothness index calculated from the road profiles using a filter pack that simulates the movement of golden ¼ car. Ratio of accumulated suspension motion to distance traveled (in/mile).
MRI: Mean IRI calculated from the IRI of two wheel paths, computed IRI values are averaged and reported as MRI (in/mile)
Profile: A profile is a two-dimensional slice of the road surface taken along an imaginary line (elevation of road) (*5*)
Profile Index (PI): A smoothness index derived from a profile provided by a profilograph. The sum of peaks and valleys falling outside a blanking band reported in (in/mile).
Profilograph: An instrument used to provide a profilograph trace.
Smoothness Histogram: A histogram developed from the continuous IRI results. The bins are assigned to coincide with the pay factor table.

1. INTRODUCTION

1.1 Objectives

Pavement smoothness is one of the most important factors to the traveling public. This reality was acknowledged with the first AASHO Road Test. More recent studies conclude that, next to congestion and safety, ride quality is the most important factor to road users (*1*), but its significance goes beyond mere public perception. Studies have also concluded that pavement smoothness has an impact on vehicle operating costs (*2*). Additionally, roads with higher initial smoothness have a greater service life (*3*). There is evidence that also suggests that pavements with higher initial smoothness stay smoother longer. Thus agency maintenance costs are less for pavements with higher initial smoothness (*1*). Pavement smoothness is one of the factors the Federal Highway Administration (FHWA) requires state DOTs to track and report. Additionally, pavement smoothness is an important factor in the new AASHTO MEPDG Pavement Design Guide, which requires design inputs of initial pavement smoothness and threshold pavement smoothness as a failure criterion.

Currently INDOT is utilizing the profile index (PI) measured by a profilograph to evaluate the smoothness of newly constructed pavement. Profilographs do not provide a true profile of the road (*4*). Smith et al. (*3*) concluded that response-type roughness measuring systems, such as the California profilograph, have inadequate repeatability, poor correlation with user response, speed sensitivity, and lack of a true profile measurement (*3*). Consequently, the data INDOT is collecting on newly constructed projects does not provide an accurate portrayal of the pavements smoothness. Furthermore, profilograph technology is slow in its data collection and subsequent analysis. INDOT has struggled for many years using this technology and is in need of updating its procedures. Also, INDOT is adopting the MEPDG which also requires pavement smoothness inputs based on international roughness index (IRI). Evaluation of the pavement smoothness during construction should also be conducted using the same index for which the pavement was designed. Additionally, INDOT currently uses IRI data collected with inertial profiles (IP) to evaluate the smoothness of pavements over the remaining life of the project. For better pavement management, initial smoothness data should also be based on the same index.

IRI as a smoothness index provides much higher correlation user response (*5*). Furthermore, inertial profiler technology has made improvements over the years including improving the procession and accuracy of profiles. Consequently, inertial profiler technology has advanced to where they may be confidently used for providing profiles for IRI calculation.

The purpose of this research is to provide INDOT draft IRI based smoothness specifications for newly constructed pavement utilizing high speed inertial profilers.

1.2 Organization

The process of developing a new IRI smoothness specification for newly constructed pavements required research and development in the following six areas (see Figure 1.1):

1. Develop Pay Factor Table
2. Develop Methodology for Calculating Smoothness Quality Assurance Adjustment of Newly Constructed Pavements

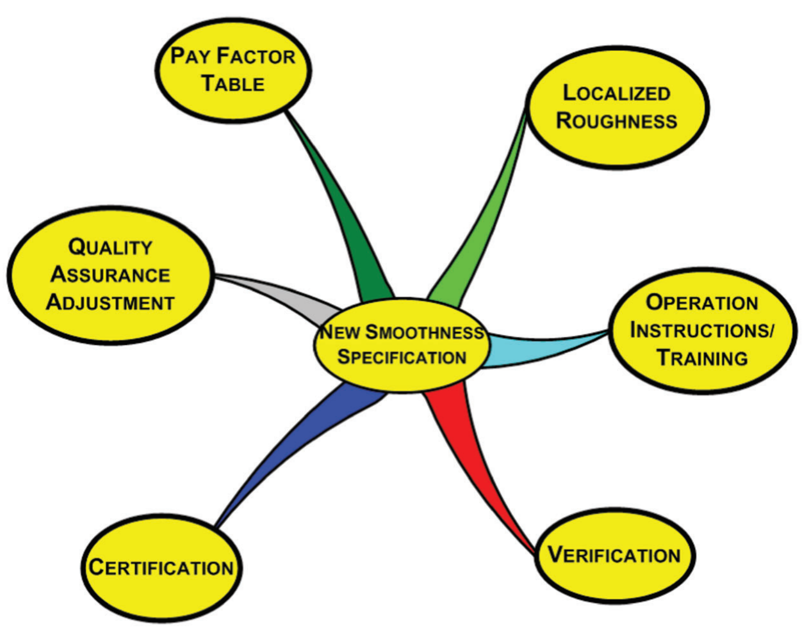

Figure 1.1 Scope of project.

3. Develop Methodology of Locating Areas of Localized Roughness (Bumps)
4. Provide Guidance of Quality Assurance through Verification
5. Develop Inertial Profiler Certification Procedures
6. Provide Guidance on IP Operation Instructions and Review Training Needs

2. DEVELOPMENT OF PAY FACTOR TABLES

The proposed pay factor table for the new smoothness quality assurance specification for HMA and PCC smoothness quality assurance is included in Table 2.1.

The development of the pay factor tables proceeded in a two stage approach. The first stage was to convert the current PI pay factor tables to IRI. The second stage was to develop pay factor tables based on IRI performance models and life cycle costs.

2.1 Pay Factor Table Conversion

Converting a PI pay factor table to IRI is flawed because of two complications. The profiles provided by the inertial profiler and profilograph are not alike and the indices calculated from the profiles are very different.

The frequency response of the profile measuring system indicates how the system responds to the changes of elevation of the road. An ideal profile measuring system would have a flat gain across all of the wavelengths significant in ride comfort. The frequency response of the profilograph is much different than that of an IP. The profilograph significantly amplifies (magnitude >1 in Figure 2.1) events with an approximate wavelength of the device (25 feet for instrument in Figure 2.1), and attenuates (magnitude <1 in Figure 2.1) events at half of the device length (12.5 feet) (see Figures 2.1 and 2.2). The line marked "desired" in Figure 2.1 represents the response of an ideal profiler. The frequency response of an inertial profiler is much closer to the desired frequency response.

The Profile Index (PI) is calculated by adding the amplitudes of the bumps and dips outside the blanking band. Currently INDOT uses a zero blanking band; therefore, the PI is calculated by adding all the bumps and dips in a given length of profilogram (*6*). IRI is calculated by putting the "true profile" through a filter pack modeling the response of a quarter car (see Figure 2.3) (gold car) to the elevation profile (*5*). The quarter car models the reaction of the car and suspension to road roughness (*5*). The two lobes of the filter represent wavelengths that cause the most ride discomfort, body bounce and axel hop; consequently, IRI is correlated to ride comfort (see Figure 2.4) (*4*).

The complications listed above have not prevented agencies from developing statistical relationships between PI and IRI. The FHWA developed relationships between IRI and PI for various pavement stratigraphies and various environmental conditions (*9*). This study utilized relationships between PI and IRI and developed this report to establish a starting point for the specification development. However these relationships must be utilized judiciously. It is unrealistic to believe that bonuses calculated using pay factor tables utilizing IRI will yield the same results of those generated utilizing PI.

The following four equations (see Equation 1) were utilized for converting the pay factor tables.

$$\begin{aligned} IRI &= 2.66543 * PI_{0.0} + 213.01 \quad & AC \\ IRI &= 2.42295 * PI_{0.0} + 301.90 \quad & AC/AC \\ IRI &= 2.40300 * PI_{0.0} + 292.93 \quad & AC/PCC \\ IRI &= 2.12173 * PI_{0.0} + 439.76 \quad & PCC \end{aligned} \tag{1}$$

The formulas were used to convert both the INDOT 2006 pay factor tables and the 2008 pay factor tables to IRI. Table 2.2 contains the PI and converted IRI HMA pay factor tables using the AC formula, and Table 2.3 contains the PI and converted HMA pay factor tables using the AC/AC formula.

Table 2.4 contains the PI and converted IRI HMA pay factor tables using the AC/PCC formula, and Table 2.5 contains the PI and converted PCC pay factor tables using the PCC formula. Notice for the 2008 converted pay factor tables bonuses will be paid out for rough pavements up to almost 100 in/mile for

TABLE 2.1
Proposed Pay Factor Table

Start IRI (in/mile)	End IRI (in/mile)	Pay Factor HMA	Pay Factor PCC
0	35	1.06	1.08
35	40	1.06	1.07
40	45	1.04	1.05
45	50	1.03	1.04
50	55	1.02	1.02
55	60	1	1.01
60	65	1	1
65	70	1	1
70	75	0.98	0.99
75	80	0.97	0.98
80	85	0.96	0.96
85	Inf	0.94	0.95

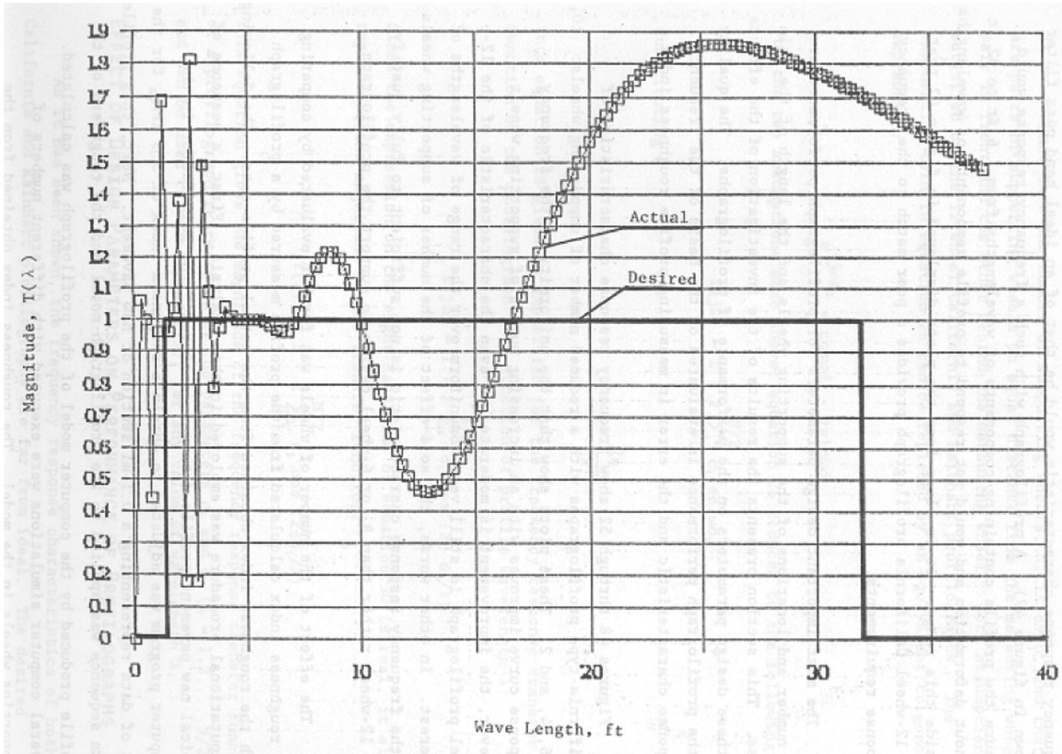

Figure 2.1 Frequency response of a profilograph (*7*).

the HMA tables and over 104 in/mile for PCC pavements. These are very lenient pay factor tables. The converted 2006 pay factor tables are more reasonable but still relatively lenient.

Scatterplots of the 2008 converted HMA pay factor tables for AC/AC formula and PCC show that the converted 2008 specification is very lenient for rough pavements (see Figure 2.5 and Figure 2.6). As shown, the overall slope of the lines for the pay factors flatten out significantly after the bonus pay factor of 1.02, and the slopes of lines for the converted 2006 pay factors are more consistent through the whole range of IRI values.

The 100% pay band for the entire group of converted pay factor tables are well above the 100% band for IRI specifications for newly constructed interstate and NHS pavements for other states (see Table 2.6). Consequently, the converted pay factor tables are more lenient than surrounding states.

2.2 Development of Pay Factor Tables

Three models were used to develop the pay factor tables for the draft specification. First, a model was

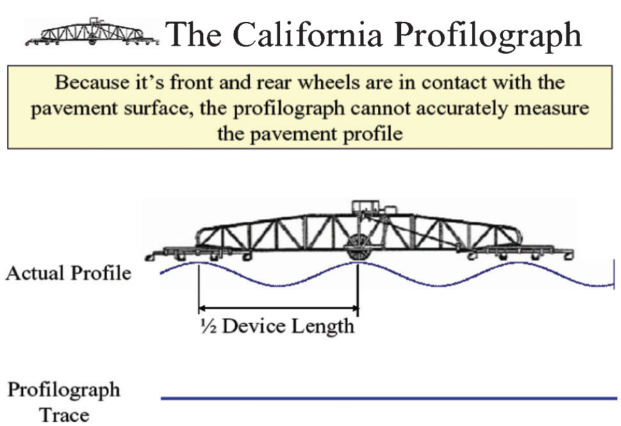

Figure 2.2 Graphic representation of profilograph and PI for half device length (*8*).

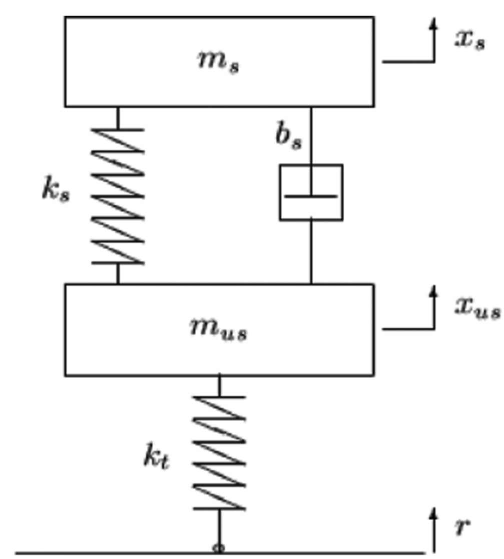

Figure 2.3 Quarter car model (*10*).

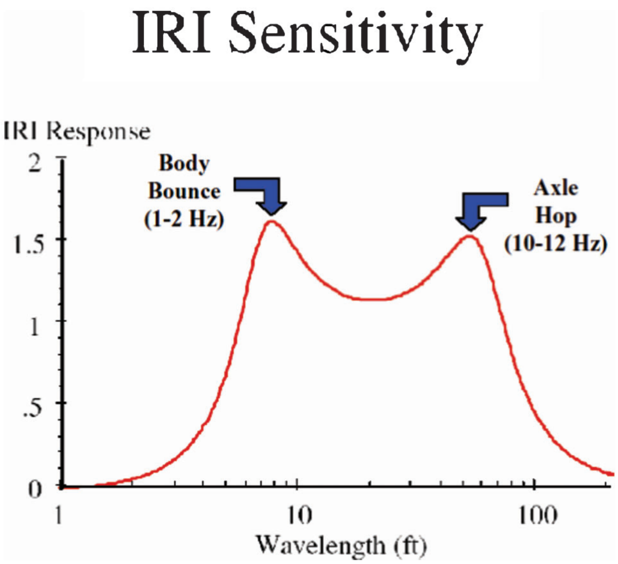

Figure 2.4 Frequency response of IRI filter (*8*).

utilized to relate the initial IRI of newly constructed pavement to the expected life of the pavement. Then life cycle cost analysis (LCCA) was used to relate costs to the expected changes in life of the newly constructed pavement. Finally, a model was developed to utilize the outputs of the previous two models to relate changes in initial IRI to changes in costs. The final model parameters were then scrutinized, and, changes were made to the inputs of the first two models until the final model yielded satisfactory results. Satisfactory results were defined as one HMA model and one PCC model yielding reasonable pay factors over a range between 30 to 90 inches per mile. Pay factor tables were then developed for this selected model. The pay factor tables were adjusted and then finalized based on the results of the quality assurance evaluation.

A four-step process was followed to develop a model between costs and initial IRI. The first step was to develop a linear model between initial IRI and the ratio of the observed pavement life verses the designed pavement life (see Figure 2.7 and section 2.4). The second step was to develop a linear relationship between the ratios of the observed pavement life verses the designed pavement life and the costs at the observed pavement life verses the costs at designed pavement life (see Figure 2.7 and section 2.5). The next step is to develop a linear relationship between the initial IRI and the ratio of the costs at designe life verses designed pavement life (see Figure 2.7). The final step was to calculate the pay factor.

TABLE 2.2
HMA IRI Pay Factor Table Converted Using the AC Formula

Profile Index (PI), in/0.1mi		2008 HMA	IRI Value, in/mi		Profile Index (PI), in/0.1mi		2006 HMA	IRI Value, in/mi	
Lower	Upper	Pay Factor	Lower	Upper	Lower	Upper	Pay Factor	Lower	Upper
0.00	1.20	1.06	13.50	45.48	0.00	0.80	1.06	13.50	34.82
1.20	1.40	1.05	45.48	50.81	0.80	1.00	1.05	34.82	40.15
1.40	1.60	1.04	50.81	56.14	1.00	1.20	1.04	40.15	45.48
1.60	1.80	1.03	56.14	61.47	1.20	1.40	1.03	45.48	50.81
1.80	2.00	1.02	61.47	66.80	1.40	1.60	1.02	50.81	56.14
2.00	2.40	1.01	66.80	77.47	1.60	2.00	1.01	56.14	66.80
2.40	3.20	1.00	77.47	98.79	2.00	2.40	1.00	66.80	77.47
3.20	3.40	0.96	98.79	104.12	2.40	2.60	0.96	77.47	82.80
					2.60	2.80	0.92	82.80	88.13

TABLE 2.3
HMA IRI Pay Factor Table Converted Using the AC/AC Formula

Profile Index (PI), in/0.1mi		2008 HMA	IRI Value, in/mi		Profile Index (PI), in/0.1mi		2006 HMA	IRI Value, in/mi	
Lower	Upper	Pay Factor	Lower	Upper	Lower	Upper	Pay Factor	Lower	Upper
0.00	1.20	1.06	19.13	48.20	0.00	0.80	1.06	19.13	38.51
1.20	1.40	1.05	48.20	53.05	0.80	1.00	1.05	38.51	43.36
1.40	1.60	1.04	53.05	57.90	1.00	1.20	1.04	43.36	48.20
1.60	1.80	1.03	57.90	62.74	1.20	1.40	1.03	48.20	53.05
1.80	2.00	1.02	62.74	67.59	1.40	1.60	1.02	53.05	57.90
2.00	2.40	1.01	67.59	77.28	1.60	2.00	1.01	57.90	67.59
2.40	3.20	1.00	77.28	96.66	2.00	2.40	1.00	67.59	77.28
3.20	3.40	0.96	96.66	101.51	2.40	2.60	0.96	77.28	82.13
					2.60	2.80	0.92	82.13	86.97

TABLE 2.4
HMA IRI Pay Factor Table Converted Using the AC/PCC Formula

Profile Index (PI), in/0.1mi		2008 HMA	IRI Value, in/mi		Profile Index (PI), in/0.1mi		2006 HMA	IRI Value, in/mi	
Lower	Upper	Pay Factor	Lower	Upper	Lower	Upper	Pay Factor	Lower	Upper
0.00	1.20	1.06	18.56	47.40	0.00	0.80	1.06	18.56	37.78
1.20	1.40	1.05	47.40	52.20	0.80	1.00	1.05	37.78	42.59
1.40	1.60	1.04	52.20	57.01	1.00	1.20	1.04	42.59	47.40
1.60	1.80	1.03	57.01	61.81	1.20	1.40	1.03	47.40	52.20
1.80	2.00	1.02	61.81	66.62	1.40	1.60	1.02	52.20	57.01
2.00	2.40	1.01	66.62	76.23	1.60	2.00	1.01	57.01	66.62
2.40	3.20	1.00	76.23	95.46	2.00	2.40	1.00	66.62	76.23
3.20	3.40	0.96	95.46	100.26	2.40	2.60	0.96	76.23	81.04
					2.60	2.80	0.92	81.04	85.84

TABLE 2.5
PCC IRI Pay Factor Table Converted Using the PCC Formula

Profile Index (PI), in/0.1mi		2008 PCC	IRI Value, in/mi		Profile Index (PI), in/0.1mi		2006 PCC	IRI Value, in/mi	
Lower	Upper	Pay Factor	Lower	Upper	Lower	Upper	Pay Factor	Lower	Upper
0.00	1.40	1.06	27.86	57.57	0.00	1.00	1.06	27.86	49.08
1.40	1.60	1.05	57.57	61.81	1.00	1.20	1.05	49.08	53.32
1.60	1.80	1.04	61.81	66.05	1.20	1.40	1.04	53.32	57.57
1.80	2.00	1.03	66.05	70.30	1.40	1.60	1.03	57.57	61.81
2.00	2.40	1.02	70.30	78.78	1.60	1.80	1.02	61.81	66.05
2.40	2.80	1.01	78.78	87.27	1.80	2.20	1.01	66.05	74.54
2.80	3.60	1.00	87.27	104.25	2.20	2.60	1.00	74.54	83.03
3.60	3.80	0.96	104.25	108.49	2.60	2.80	0.96	83.03	87.27
					2.80	3.00	0.92	87.27	91.52

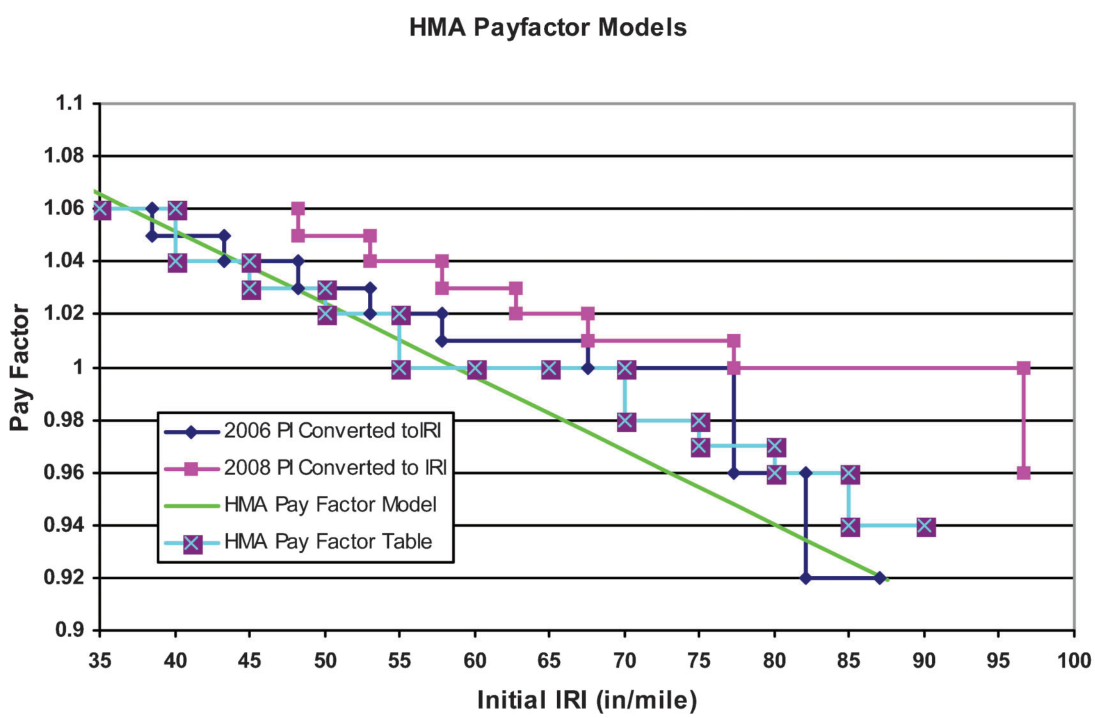

Figure 2.5 Pay factor lines: 2006 and 2008 converted HMA using AC/AC model.

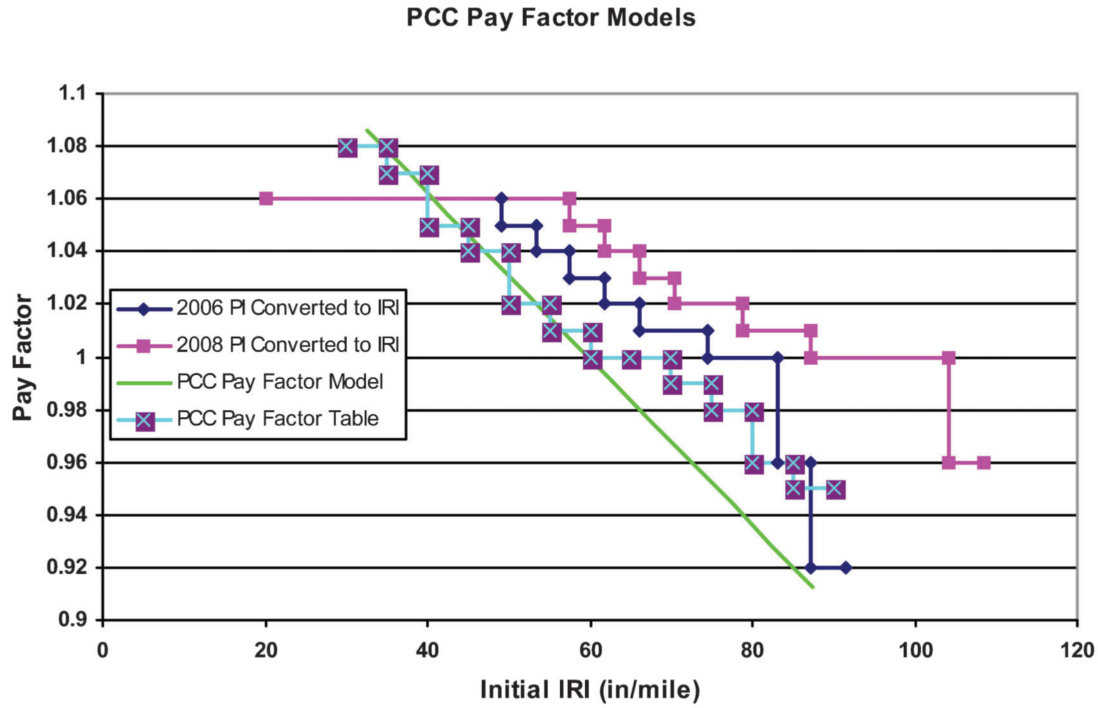

Figure 2.6 Pay factor lines: 2006 and 2008 converted PCC using PCC model.

The process of settling on a final model to use for developing the pay factor table is described in flow chart form in Figure 2.8. A number of IRI and LCCA models were developed for HMA and PCC pavements. The four inputs of the models were adjusted until the pay factor model produced reasonable quality assurance smoothness bonus pay out. The equation of the pay factor model utilized for HMA pavements follows (see Equation 2):

$$\begin{aligned} y &= -0.0028x + 1.16 \\ y &= \text{HMApayfactor} \\ x &= \text{IRI} \end{aligned} \quad (2)$$

The equation of the pay factor model utilized for PCC pavements follows (see Equation 3):

TABLE 2.6
Surrounding States Specifications

State	PCC Low 100% (in/mile)	PCC High 100% (in/mile)	Corrective Action (in/mile)	HMA Low 100% (in/mile)	HMA High 100% (in/mile)	Corrective Action (in/mile)
INDOT Proposed	60	70	90	55	70	90
INDOT 2006 Converted	75	83		67	76	
INDOT 2008 Converted	87	104		76	95	
MI	0	75	75	0	75	75
MI	0	125	125	0	125	125
KY	60	80	91	40	70	81
KY	65	85	96	46	80	91
OH	60	70	95	60	70	95
MO>45	54	80	80	54	80	80
MO<45	67	134	134	67	134	134
PA	60	70	70	60	70	70
PA	70	90	90	70	90	90
WI	35	60	75	35	60	75
WI	55	85	100	55	85	100
WI		>75			>75	
WV	60	65	99	60	65	99

State pavement specifications found at www.smoothpavements.com (*1*).

$$
\begin{aligned}
&\textit{Step 1} \quad \textit{Develop IRI Linear Model}\\
&y_{iri} = m_1 x_{iri} + b_1 \quad eq(1)\\
&y_{iri} = \frac{\textit{Observed Pavement Life}}{\textit{Designed Pavement Life}}\\
&x_{iri} = \textit{initial} \quad \textit{IRI}\\
\\
&\textit{Step 2} \quad \textit{Develop Linear Cost Model}\\
&y_c = m_2 x_c + b_2 \quad eq(2)\\
&y_c = \frac{\textit{Costs at Observed Pavement Life}}{\textit{Costs at Designed Pavement Life}}\\
&x_c = \frac{\textit{Observed Pavement Life}}{\textit{Designed Pavement Life}}\\
\\
&\textit{Step 3 Use following realtionship and}\\
&\textit{solve for } y_c \textit{ in tems of } x_{iri}\\
&x_c = y_{iri} \quad eq(3)\\
\\
&\textit{Substitute } eq(1) \textit{ in } eq(2)\\
&y_c = m_2(m_1 x_{iri} + b_1) + b2\\
&m_3 = m_2 m_1 \quad b_3 = m_2 b_1 + b_2\\
\\
&y_c = m_3 x_{iri} + b_3\\
\\
&\textit{Step 4 calculate pay factor}\\
\\
&PF = 1 - (y_c - 1)
\end{aligned}
$$

Figure 2.7 Model development used for to determine pay factor tables.

$$
\begin{aligned}
y &= -0.0032x + 1.1886\\
y &= \text{PCCpayfactor} \qquad (3)\\
x &= \text{IRI}
\end{aligned}
$$

Tables were constructed from the pay factor models by selecting a starting IRI, and ending IRI, and a cell size for the table. Next, the model was utilized to determine the pay factor value for mid-point value of each cell. This value was rounded to the nearest. 01 and assigned to the table cell. Figure 2.9 and Figure 2.10 contains a scatter plot of the original HMA and PCC pay factor tables respectively.

The resulting pay factor tables were adjusted. The HMA table was adjusted to decrease the impact of incentive for the smoothest pavements, and decrease the disincentive for rough pavements. This was done making the maximum pay factor 1.06, increasing the 1.0 pay band and making the table symmetric about the 1.0 pay band (see Figure 2.9). The PCC table was adjusted my increasing the 1.0 pay band and making the pay table symmetric about the 1.0 band to decrease the disincentive for rough pavements (Figure 2.10).

Table 2.7 contains the original and modified pay factor tables for both HMA and PCC pavement.

The change from the original to modified pay factor tables was brought about by looking at the smoothness assurance bonus and bonus percentages for different road segments. The smoothness bonus percentage is the percentage of the final material costs that would be paid out for the smoothness bonus. For example, a smoothness bonus percentage of 1.03 would lead to a smoothness bonus of an additional 3% of the material costs. For the HMA pavements the differences were determined in three steps. The first step was to increase the 100% pay band; this was done to decrease the disincentive for rough pavements. The second step was to make the table symmetric about the 100% pay band; this was also done to decrease the disincentive for rougher pavements. As shown in Table 2.8, the bonus calculated using the original pay factor table was much lower than the PI bonus for rougher HMA pavements. Notice the bonus paid out for SR-64 and SR-56 is much higher using the modified pay factor table. The methodology used to calculate the bonus is described in the next chapter.

The third step was to decrease the maximum pay factor from 1.07 to 1.06 ending in the modified pay factor tables. This was done to decrease the overall smoothness bonus percentage. The smoothness bonus percentages were calculated for each step of the evaluation (see Table 2.9). This was done for two large HMA populations, as well as the selected road sections. The HMA ALL population consists of 640 miles of IRI data collected on newly constructed HMA pavements between 2008 and 2010. A majority of the data was collected for smoothness awards; the remainder of the data was specifically collected for this study. The HMA 2010 population, 223 miles, contains data collected in 2010. Based on the HMA ALL population, lowering the pay factor ceiling from 1.07 to 1.06 would drop the smoothness bonus $3,570 for every $1M spent on HMA materials. The drop would be $4,420 using the HMA 2010 population.

Based on the HMA ALL population, changing from the original to the modified pay factor table will cost an additional $484 for every $1M in construction materials; however, based on the HMA 2010 population changing to the modified pay factor table would save $1800 for every $1M.

For the PCC specification a two-step process was followed. The first step was to increase the 100% pay band; this was done to decrease the disincentive for rough pavements. The second step was to make the table symmetric about the 100% pay band; this was also done to decrease the disincentive for rougher pavements. The pavement bonus calculated using the original pay factor table was much smaller for rougher pavements (see Table 2.10). Notice for the rougher pavements there was a penalty assessed (see Table 2.10). The smoothness bonus percentages were calculated for each step of the evaluation (see Table 2.9). This was done for one large PCC population, as well as the selected road sections. The PCC 2010 population consists of 41 miles of IRI data collected on newly constructed PCC pavements between in 2010. IRI data collected in 2010 was collected using RoLine line lasers, and IRI data collected in earlier years was collected using dot lasers.

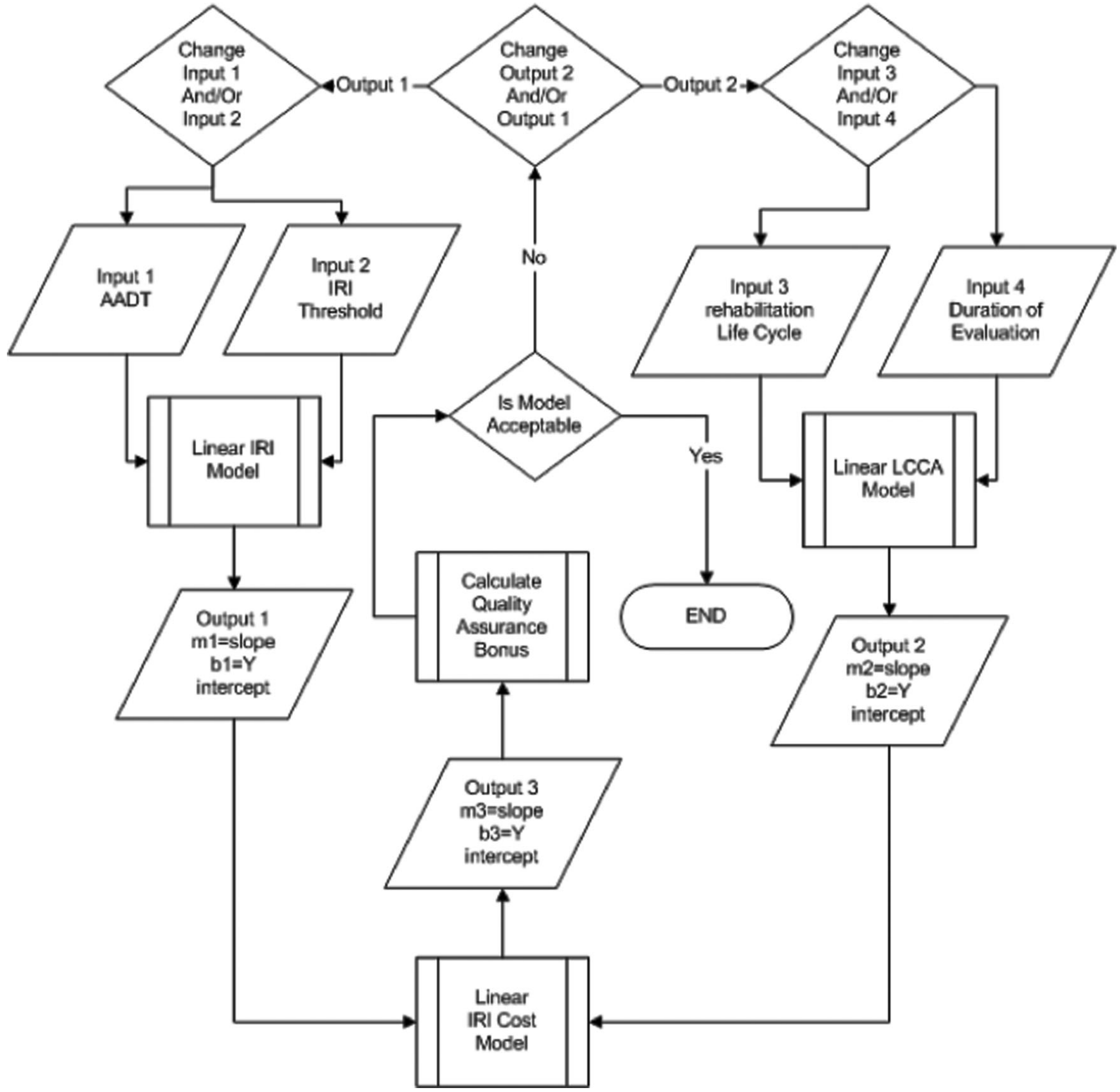

Figure 2.8 Model adjustment flow chart for determining pay factor tables.

There is higher variability in IRI data collected on PCC pavement using dot lasers; consequently, data collected in early years is not presented here.

Based on the bonus percentage results from the 2010 PCC population, changing from the original to the modified pay factor table will cost an additional \$13,700 for every \$1M in material costs, but if the original pay factor table is used contractors would pay \$5,356 in penalties for every \$1M in material costs (see Table 2.11).

2.3 Smoothness Bonus Comparison

The difference between smoothness bonuses calculated using the proposed specification and the current specification varied significantly. For a number of pavement sections, smoothness bonuses calculated using the proposed IRI specification are relatively close to bonuses calculated using the current specification (2008 PI) for HMA pavements (see Figure 2.11). Note the smoothness bonus values for the pavement sections with an average MRI less than 47 in/mile are similar (see Figure 2.11). However, note that the proposed specification paid out about twice the bonus of the current specification for the section with an mean MRI of 47 in/mile, and the proposed specification paid out on half the bonus using the current specification for the pavement section with an average MRI of 58 in/mile (see Figure 2.11).

One trend visible in the HMA data is that the proposed specification pays out less in smoothness bonus for rougher pavements. The smoothness bonus calculated using the proposed specification is visibly less than the bonus calculated using the current specifications for pavements with average MRI values above 57 in/mile (see Figure 2.11).

For PCC pavements the smoothness bonus calculated using the proposed specification is higher than the smoothness bonus calculated using current specification for smooth pavements but much smaller for

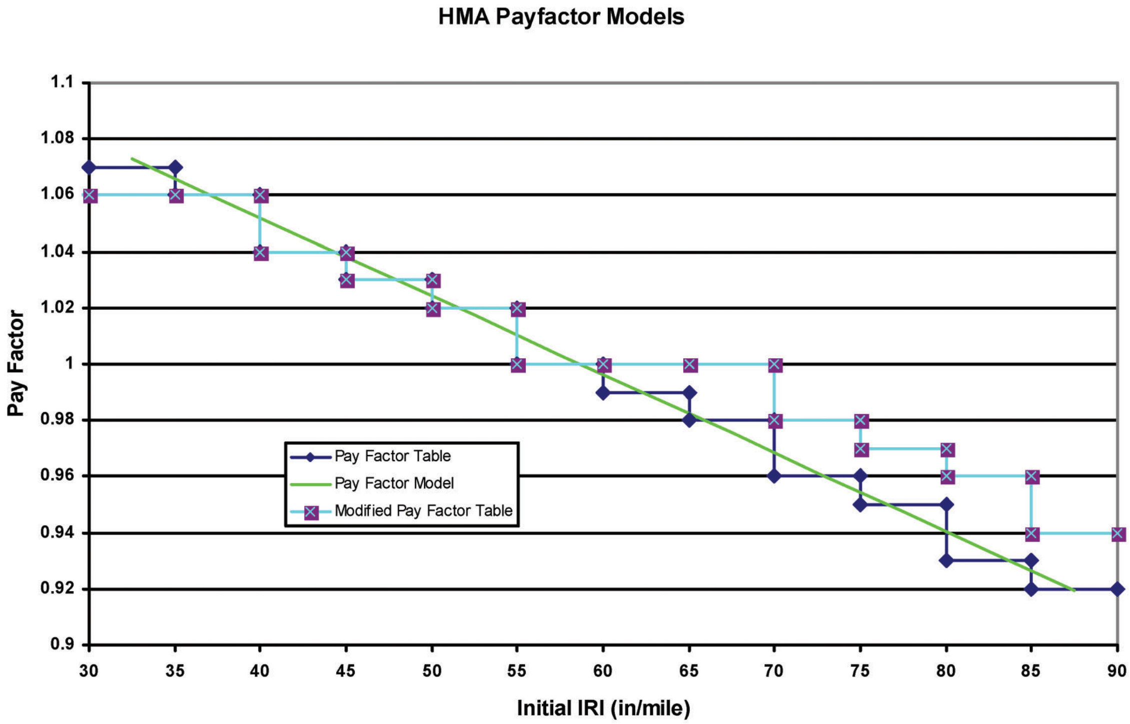

Figure 2.9 HMA pay factor model, pay factor table and modified pay factor table.

rougher pavements (see Table 2.10). Notice that the smoothness bonus calculated using the proposed specification for US-24 (average MRI 48 in/mile) is about twice the bonus calculated using the current specification, but the smoothness bonus calculated using the proposed specification for US-231 (average MRI 60 in/mile) is about one half the bonus calculated using the current specification (see Table 2.10).

Smoothness bonuses calculated using the proposed specification for a number of pavement sections were compared with bonuses calculated using the specifications of states in located close to Indiana. The comparison

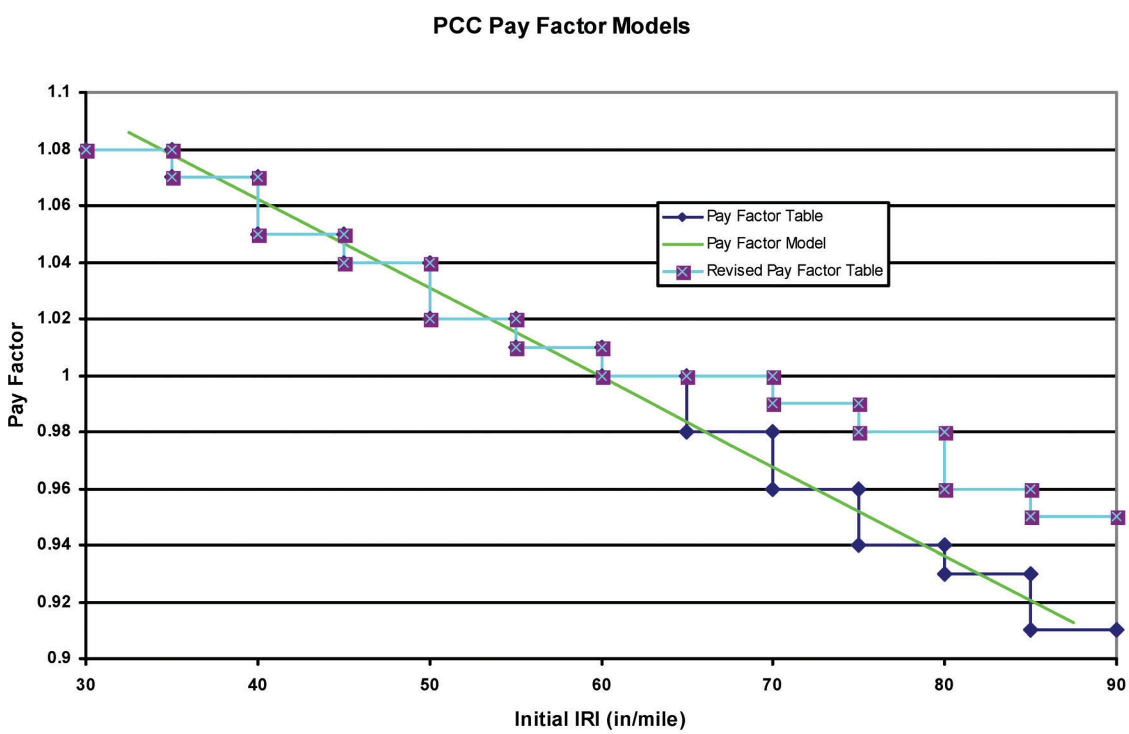

Figure 2.10 PCC pay factor model, pay factor table and modified pay factor table.

TABLE 2.7
Pay Factor Tables for HMA and PCC

Start IRI (in/mile)	End IRI (in/mile)	HMA Original Pay Factor	HMA Modified Pay Factor	PCC Original Pay Factor	PCC Modified Pay Factor
0	35	1.07	1.06	1.08	1.08
35	40	1.06	1.06	1.07	1.07
40	45	1.04	1.04	1.05	1.05
45	50	1.03	1.03	1.04	1.04
50	55	1.02	1.02	1.02	1.02
55	60	1	1	1.01	1.01
60	65	0.99	1	1	1
65	70	0.98	1	0.98	1
70	75	0.96	0.98	0.96	0.99
75	80	0.95	0.67	0.94	0.98
80	85	0.93	0.96	0.93	0.96
85	Inf	0.92	0.94	0.91	0.95

TABLE 2.8
HMA Pay Factor Table Bonus Comparison

Road	AVG MRI (in/mile)	Bonus Modified Pay Factor	Bonus Pay Factor	Bonus Expanded 100% Band	Bonus Symmetric Expanded 100% Band	Bonus Modified-Original	Bonus 2008 PI	Bonus 2006 PI
US-50	28	$3,165	$3,626	$3,635	$3,639	-$461	$3,337	$3,278
I-74	43	$4,367	$4,591	$4,681	$4,808	-$224	$4,766	$2,970
US-41	47	$15,888	$15,980	$16,455	$17,253	-$92	$7,295	-$2,432
SR-64	58	$3,893	$2,218	$2,797	$4,259	$1,674	$7,950	$3,769
SR-56	70	-$429	-$1,191	-$1,041	-$374	$761	$148	-$2,031
		Step 3		Step 1	Step 2			

TABLE 2.9
HMA Smoothness Bonus Percentages

Road/ Population	AVG MRI (in/mile)	Bonus Percentage Modified Pay Factor	Bonus Percentage Pay Factor	Bonus Percentage Expanded 100% Band	Bonus Percentage Symmetric Expanded 100% Band	Bonus Percentage Modified-Original	Bonus Percentage Difference Using 1.06 Ceiling
HMA total	49	1.030	1.029	1.031	1.034	4.84E-04	3.57E-03
HMA 2010	44	1.038	1.040	1.041	1.043	-1.80E-03	4.42E-03
US-50	28	1.057	1.065	1.065	1.065	-8.29E-03	8.53E-03
I-74	43	1.040	1.042	1.043	1.044	-2.05E-03	4.05E-03
US-41	47	1.034	1.034	1.035	1.037	-1.97E-04	2.92E-03
SR-64	58	1.013	1.007	1.009	1.014	5.54E-03	1.21E-03
SR-56	70	0.994	0.984	0.986	0.995	1.03E-02	7.55E-04
		Step 3		Step 1	Step 2		

TABLE 2.10
PCC Pay Factor Table Bonus Comparison

Road	AVG MRI (in/mile)	Bonus Modified Pay Factor	Bonus Pay Factor	Bonus Expanded 100% Band	Bonus Modified Original	Bonus 2008 PI
US-24	48	$12,308	$11,263	$11,561	$1,044	$6,563
US-231	60	$7,310	$1,972	$2,965	$5,337	$14,266
US-31	65	$883	-$1,545	-$1,178	$2,428	NA
I465AirS	74	-$3,094	-$12,606	-$11,822	$9,511	NA
I465AirN	77	-$1,826	-$4,980	-$4,728	$3,155	NA
US-20	80	-$4,061	-$8,742	-$8,505	$4,681	NA
I465ALL	87	-$2,333	-$7,582	-$7,189	$5,249	NA

TABLE 2.11
PCC Smoothness Bonus Percentage

Road/Population	AVG MRI (in/mile)	Bonus Percentage Modified Pay Factor	Bonus Percentage Pay Factor	Bonus Percentage Expanded 100% Band	Bonus Percentage Modified Original
PCC 2010	65	1.008	0.995	0.996	-1.37E-02
US-24	48	1.038	1.034	1.035	-3.18E-03
US-231	60	1.014	1.004	1.006	-9.94E-03
US-31	65	1.005	0.991	0.993	-1.35E-02
I-465	74	0.993	0.973	0.974	-2.06E-02
I-465	77	0.987	0.965	0.967	-2.23E-02
US-20	80	0.991	0.969	0.971	-2.13E-02
I-465	87	0.976	0.949	0.951	-2.72E-02

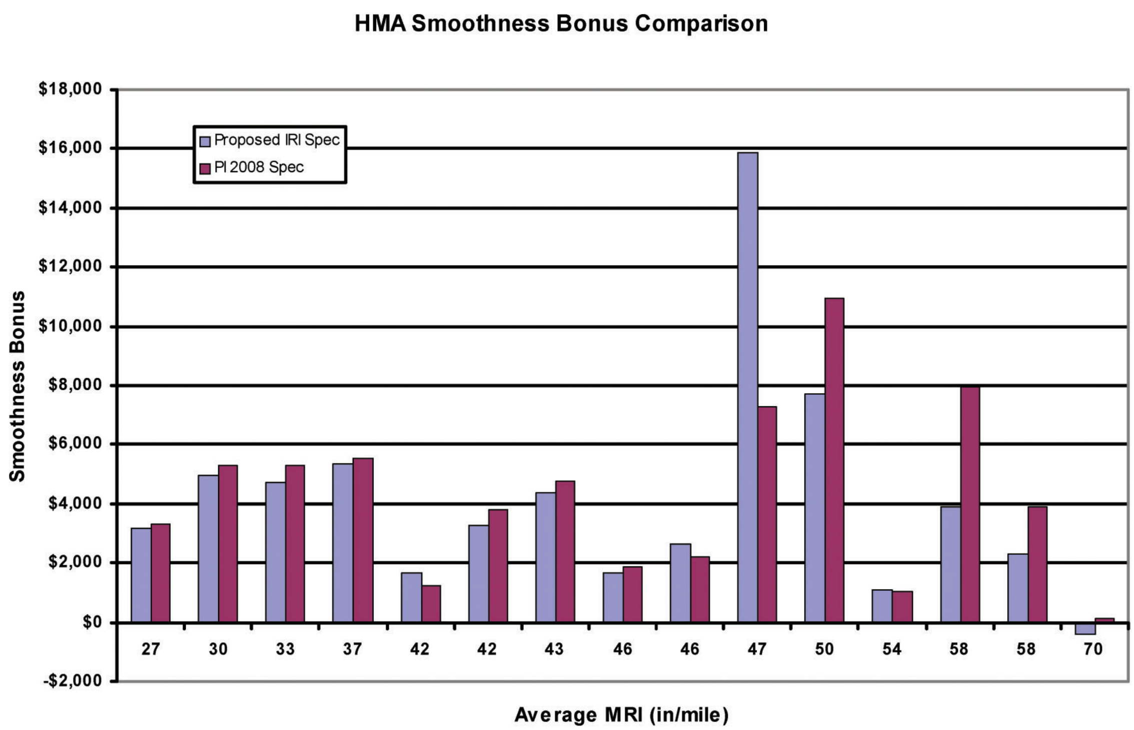

Figure 2.11 Comparison of smoothness bonus for proposed specification and current specification.

includes Ohio (ODOT), Kentucky (KDOT), Wisconsin (WISDOT), and Minnesota (MNDOT) (*1*). INODOT is the only state in the comparison that bases the bonus as a percentage of the material costs. The remaining states access a fixed dollar amount for each cell of the pay factor tables. Furthermore, INDOT penalizes for all pavement IRI values, the remaining states do not penalize for sections of pavement that require corrective action. A number of these states have more than one specification depending on the pavement classification.

Overall for HMA pavements the smoothness bonuses calculated with the proposed specification are small compared with those of the other states (see Figure 2.12 and Figure 2.13). For the roughest pavement section the INDOT smoothness bonus is noticeably higher that for the other states (see Figure 2.13).

For rougher pavements, there is significant difference in the smoothness bonuses for the different pavement classifications for the other states (see Figure 2.12 and Figure 2.13). For pavements with an average MRI above 40 in/mile the WISDOT 1 specification pays out much less than the WISDOT 2 specification (see Figure 2.12 and Figure 2.13). The main difference between WISDOT 1 HMA pavements and WIDOT 2 HMA pavements is the number of opportunities to improve the pavement smoothness. The specification is more conservative for multi-lift pavements.

For smooth PCC pavements, the INDOT smoothness bonus pays more than all other states except MNDOT (see Figure 2.14). For rougher PCC pavements the INDOT specification penalizes more than all other states except ODOT (see Figure 2.14).

2.4 Modeling the Change in Pavement Life due to Initial IRI

INDOT has developed relationships estimating the future IRI of a pavement based on the initial IRI of the pavement and the average daily truck traffic for flexible pavements and rigid pavements. These models were developed from PMS data (see Equation 4).

$$X_{flex} = \frac{\log(IRI_x) - \log(IRI_0)}{\log\left[1.015 + \frac{\log_{10}(ADTT)}{100}\right]}$$

$$X_{pcc} = \frac{\log(IRI_x) - \log(IRI_0)}{\log\left[1.015 + 0.4 \cdot \left[\frac{\log_{10}(ADTT)}{100}\right]\right]}$$

$$\begin{aligned} &X = Observed\ Pavement\ Life \\ &ADTT = Average\ Daily\ Truck\ Traffic \\ &IRI_0 = Initial\ IRI \\ &IRI_x = IRI\ Threshold \\ &flex = \text{flexiblepavement} \\ &pcc = \text{rigidpavement} \\ &thin = \text{thinoverlay} \\ &struct = \text{structuraloverlay} \end{aligned} \tag{4}$$

The linear model between the initial IRI and the ratio of the observed pavement life verses the designed

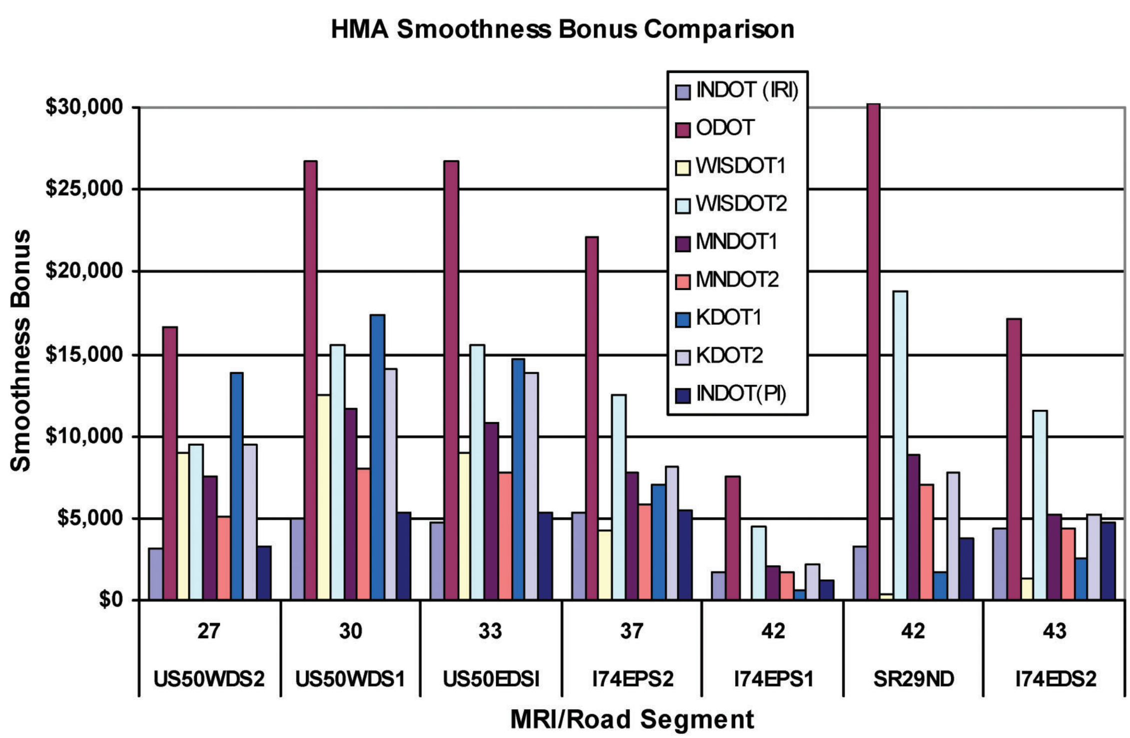

Figure 2.12 HMA smoothness bonus comparison with other DOTs.

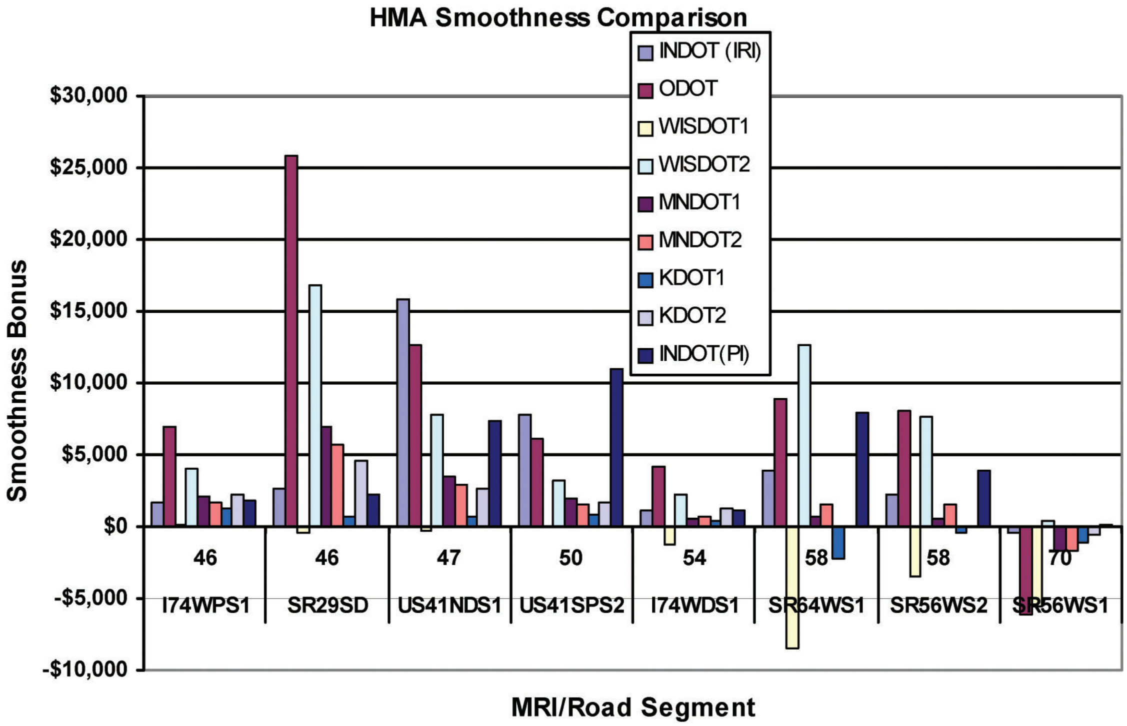

Figure 2.13 HMA smoothness bonus comparison other DOTs.

pavement life was developed for this study. The first step was to select an IRI threshold triggering rehabilitation. The second step was to select a range of IRI values and a range of AADT values to plot. The third step was to use Equation 4 and plot the initial IRI verses the ratio of the observed pavement life verses the designed pavement life. The last step was to use regression to determine a best fit line through the data set. 160 in/mile was selected as the IRI threshold.

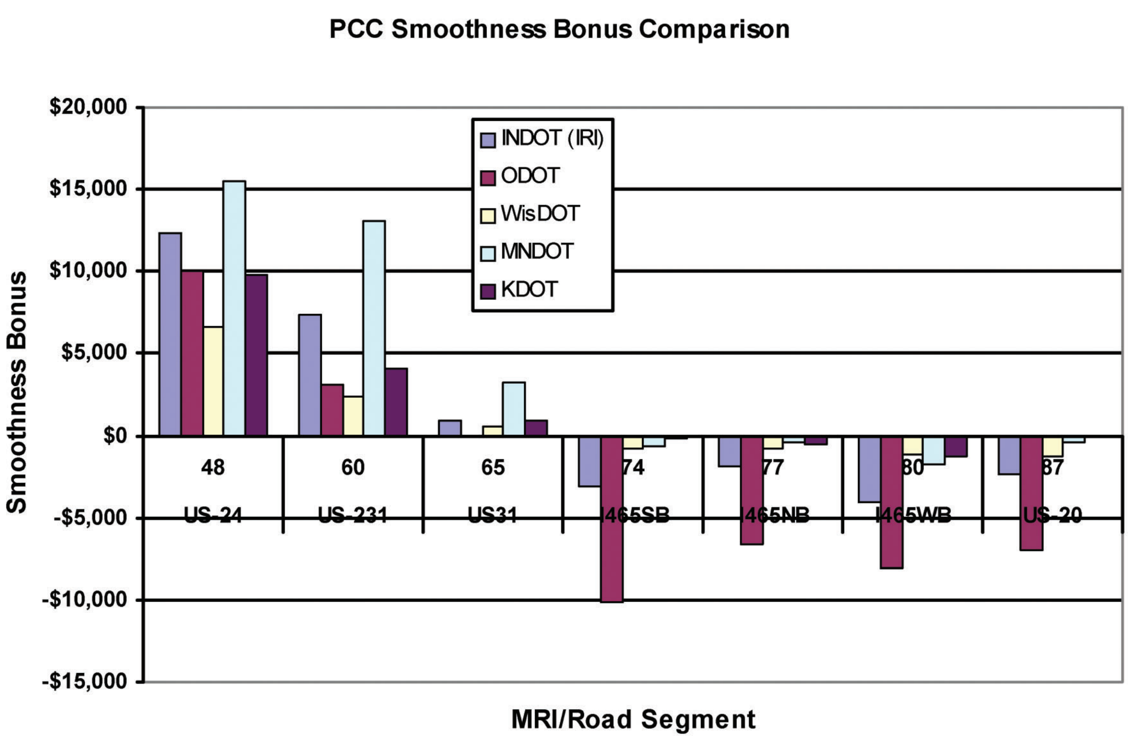

Figure 2.14 PCC smoothness bonus comparison other DOTs.

For the HMA model a design life of 20 years was selected, AADT values between 250 and 40,000, and initial IRI values between 30 in/mile and 100 in/mile were used to develop the dataset (see Figure 2.15). For the PCC model a design life of 30 years was selected, AADT values between 4,000 and 40,000, and initial IRI values between 45 in/mile and 100 in/mile were used to develop the data set (see Figure 2.16). Note each curve of green points represents the data for one AADT value and the selected initial IRI data range, and the black line represents the regression line (see Figure 2.15 and Figure 2.16).

The IRI linear regression model for HMA is included as Equation 5:

$$
\begin{aligned}
y &= -0.0159x + 1.9613 \\
x &= \text{initialIRI} \\
y &= \text{observedpavementlife}/\text{designedpavementlife}
\end{aligned} \tag{5}
$$

The linear IRI regression model for PCC is included as Equation 6:

$$
\begin{aligned}
y &= -0.0117x + 1.7057 \\
x &= \text{initialIRI} \\
y &= \text{observedpavementlife}/\text{designedpavementlife}
\end{aligned} \tag{6}
$$

2.5 LCCA Analysis

Life cycle cost analysis (LCCA) was used to relate costs to the expected changes in life of the newly constructed pavement. A linear relationship between the ratios of the observed pavement life verses the designed pavement life and the costs at the observed pavement life verses the costs at designed pavement life was developed using LCCA. The spreadsheet developed as part of a previous JTRP study for INDOT was utilized to do the LCCA (*11*).

Four case studies were conducted as part of this study. The pavement preservation/rehabilitation strategies selected for each of these cases based off the strategies developed by Lamptey et al. (*11*). Costs were evaluated for three HMA cases and one PCC case. The parameters associated with the selected preservation/rehabilitation strategies are included in Table 2.12 and Table 2.13. Cost ratios not costs were the results utilized in the study; consequently, the actual costs are not important as long as the relationship between the costs is relevant.

Figure 2.17 is a cash flow diagram of HMA case 2 where the initial pavement life (observed pavement life at 10 years) is equal to the designed life – 10 years, the designed life (observed pavement life 20 years), and the designed life + 10 years (observed life 30 years).

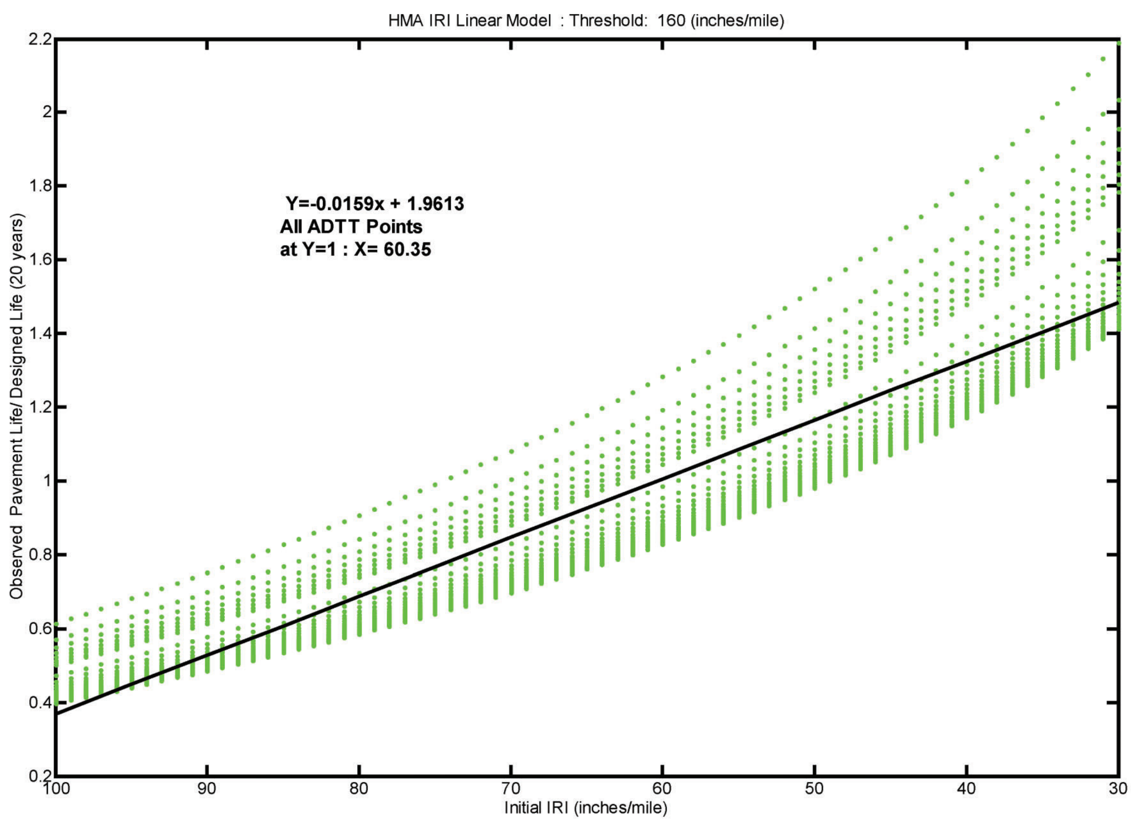

Figure 2.15 HMA IRI linear model.

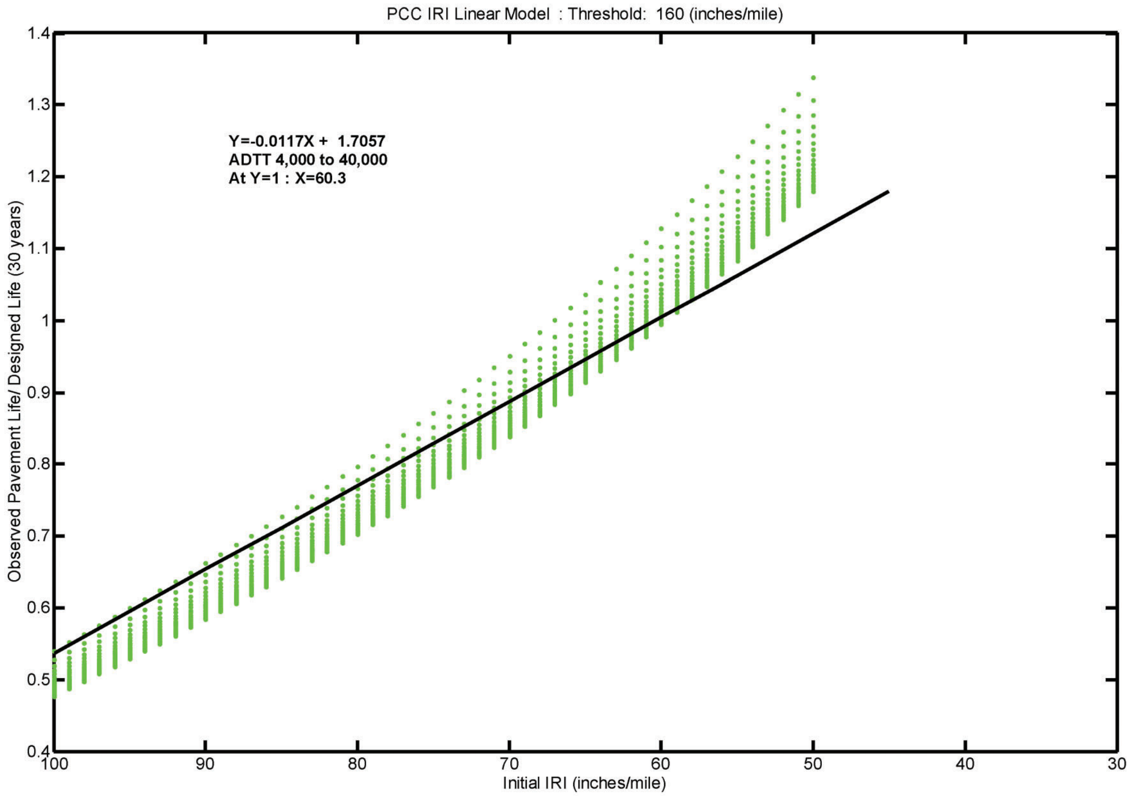

Figure 2.16 PCC IRI linear model.

TABLE 2.12
LCCA Parameters for HMA Pavements Case 2 and Case 3

HMA Case 2	Life Years	Cost ($1,000)	HMA Case 3	Life Years	Cost ($1,000)
New HMA	20	$4,114	New HMA	20	$4,114
Maintenance		$76	Maintenance		$76
Functional	15	$1,613	Functional	15	$1,613
Maintenance		$76	Maintenance		$76
PM	8	$790	PM	15	$790
Maintenance		$76	Maintenance		$76
New HMA	20	$4,114	New HMA	20	$4,114
Maintenance		$76	Maintenance		$76
Total	63	$10,857	Total	70	$10,857

TABLE 2.13
LCCA Parameters for HMA Thin Overlay Case 1 and PCC Case 1

PCC Case 1	Life Years	Cost ($1,000)	Overlay Case 1	Life Years	Cost ($1,000)
New PCC	30	$5,015	PM	8	$1,246
Maintenance		$82	Maintenance		$118
Functional	15	$1,620	Structural	15	$3,500
Maint		$76	Maintenance		$118
PM	8	$804	PM	8	$1,246
Maintenance		$76	New	20	$6,891
New HMA	20	$4,114	Maintenance		$118
Maintenance		$76	Functional	15	$2,634
			Maintenance		$118
Total	73	$11,862	Total	66	$15,989

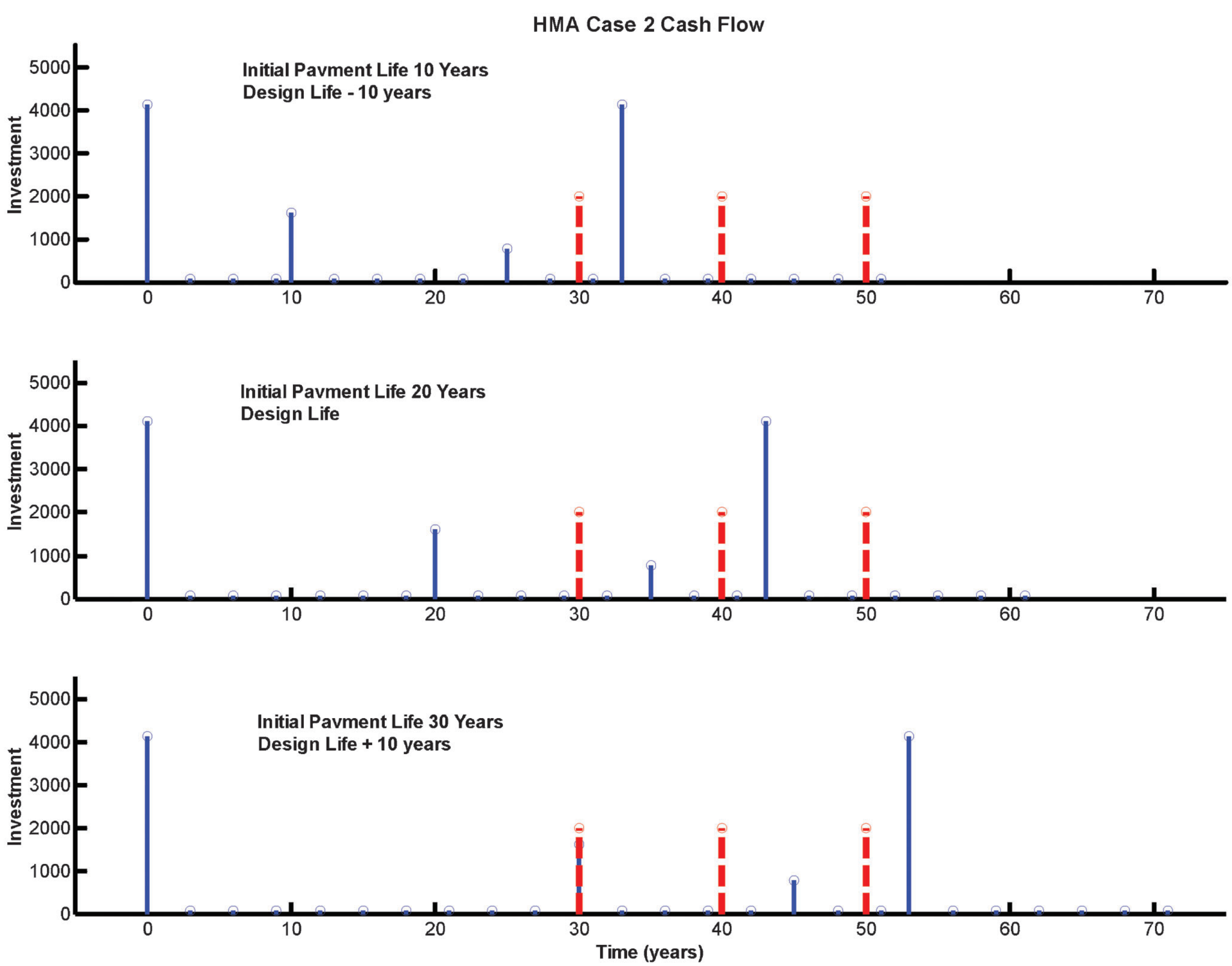

Figure 2.17 HMA Case 2 cash flow: red vertical lines LCCA evaluation periods.

Figure 2.18 is a cash flow diagram for HMA case 3 for the same initial pavement life values.

Figure 2.19 is a cash flow diagram of HMA overlay case 1 where the initial pavement life (observed pavement life at 4 years) is equal to the designed life – 4 years, the designed life (observed pavement life 8 years), and the designed life + 4 years (observed life 12 years). Figure 2.20 is a cash flow diagram of PCC case 1 where the initial pavement life (observed pavement life at 20 years) is equal to the designed life – 10 years, the designed life (observed pavement life 30 years), and the designed life + 10 years (observed life 40 years).

A four-step process was followed to determine the linear model for each of the four case studies. The first step was to select a range of observed pavement life values and LCCA evaluation time periods. The designed pavement life was selected as one of the values, for example 30 years was one of the observed pavement life values for PCC. The observed pavement life values selected for HMA cases 2 and 3 were 10 to 30 years in two year increments with 20 years as the designed life, and 4 to 12 in two year increments with 8 years as the designed life for HMA overlay 1. The observed pavement life values selected for the PCC pavement were 20 to 40 years in two year increments. The LCCA evaluation periods for HMA cases 2 and 3 were 30 to 50 years in two year increments, and 12 to 30 years in two year increments for HMA overlay case1. For PCC pavements the LCCA evaluation periods were 40 to 50 years in two year increments. For the second step one cost was determined for each observed pavement life value for each selected evaluation period. The third step was to divide the cost point value by the cost value determined for the designed pavement life, and then divide the observed pavement life value of the cost point by the designed pavement life. The results for

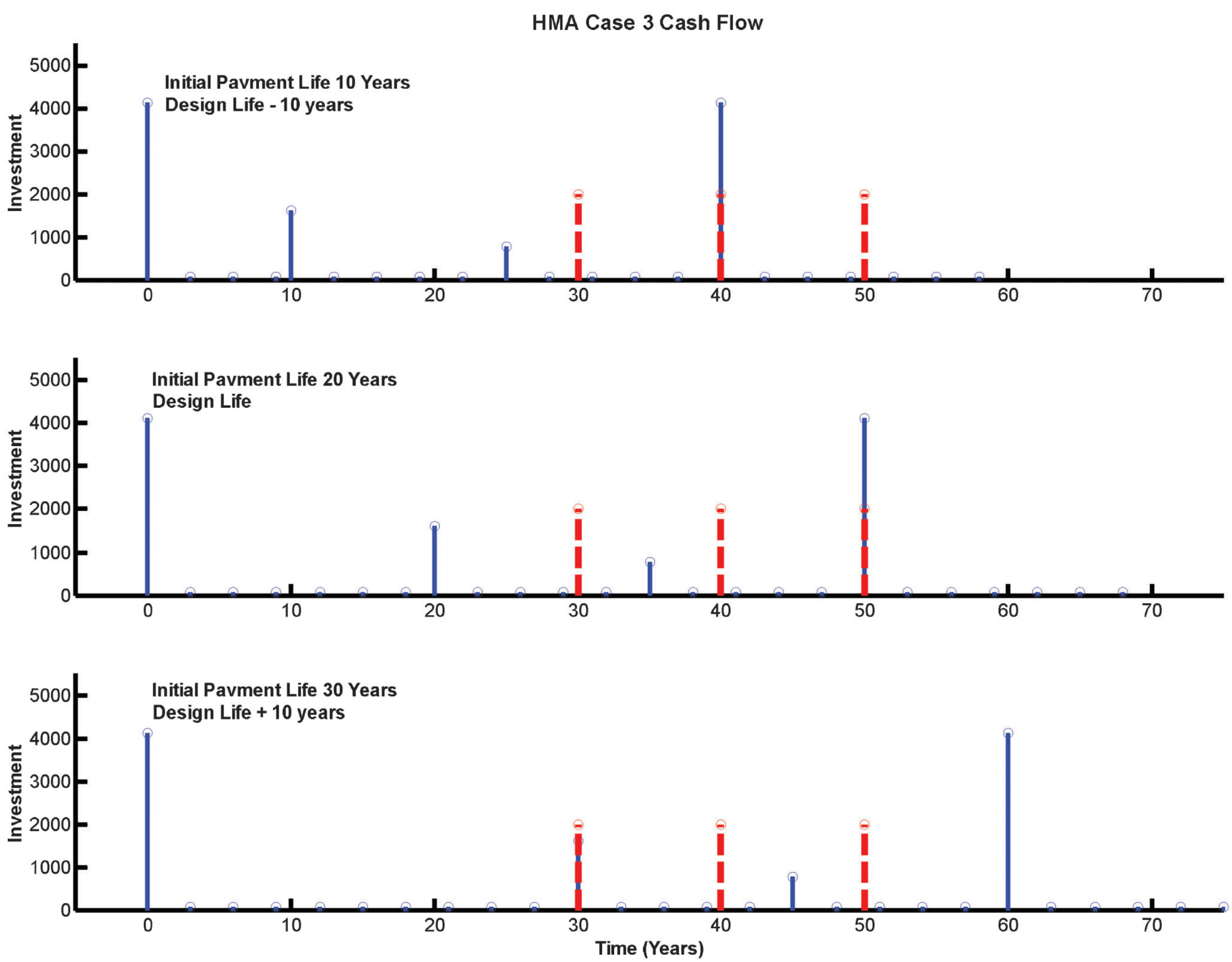

Figure 2.18 HMA Case 3 cash flow: red vertical lines LCCA evaluation periods.

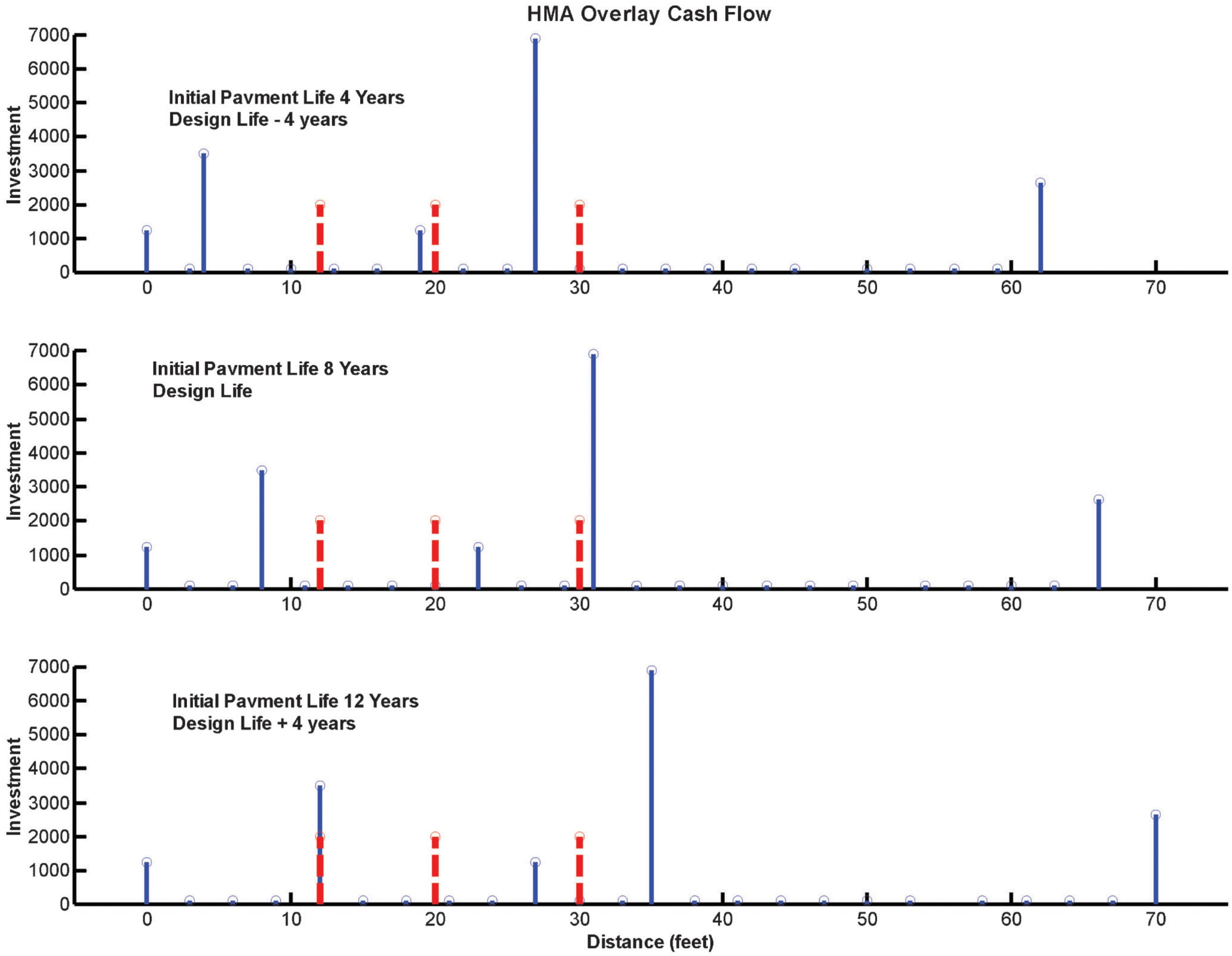

Figure 2.19 HMA Overlay 2 cash flow: red vertical lines LCCA evaluation periods.

HMA case 1 and case 2 are included in Table 2.14. The final step was to plot the developed ratios and use regression to determine a best fit linear model through the points.

This regression model was the linear relationship between the ratios of the observed pavement life verses the designed pavement life and the costs at the observed pavement life verses the costs at designed pavement life utilized for developing the pay factor tables.

A sensitivity study was conducted in order to examine the effect of the LCCA evaluation time period and the rehabilitation strategy on the model. Figure 2.21 is a plot of the data sets for HMA case 3 for each of the LCCA time periods. Note the vertical spread of the points at each X location increases with distance from the designed pavement life; therefore, model sensitivity to the LCCA time period increases with an increase or decrease in the observed pavement life (see Figure 2.21). The models for 30, 40, and 50 year LCCA evaluation period are included in the plot, note there is significant difference in the linear models. The Model for the 40 year evaluation for the Case 2 HMA is also included in the plot note there is a noticeable difference between the Case 2 and Case models. Figure 2.22 is a plot of the data sets for PCC for each of the LCCA time periods.

There is significant variability in the HMA overlay models for different time periods (see Figure 2.23). The vertical spread of the data sets is much larger for this case than that of the data sets for the HMA Case 1 and Case 2 or the PCC Case (see Figure 2.21, Figure 2.22, and Figure 2.23). The overlay model for 20 years is included in Figure 2.21 note the difference in the model is noticeable, the slope is higher and the y-intercept is larger (see Figure 2.21).

The Case 3 HMA model evaluated at 40 years was the model selected to be used for developing the HMA pay factor tables (see Equation 7 and Figure 2.24):

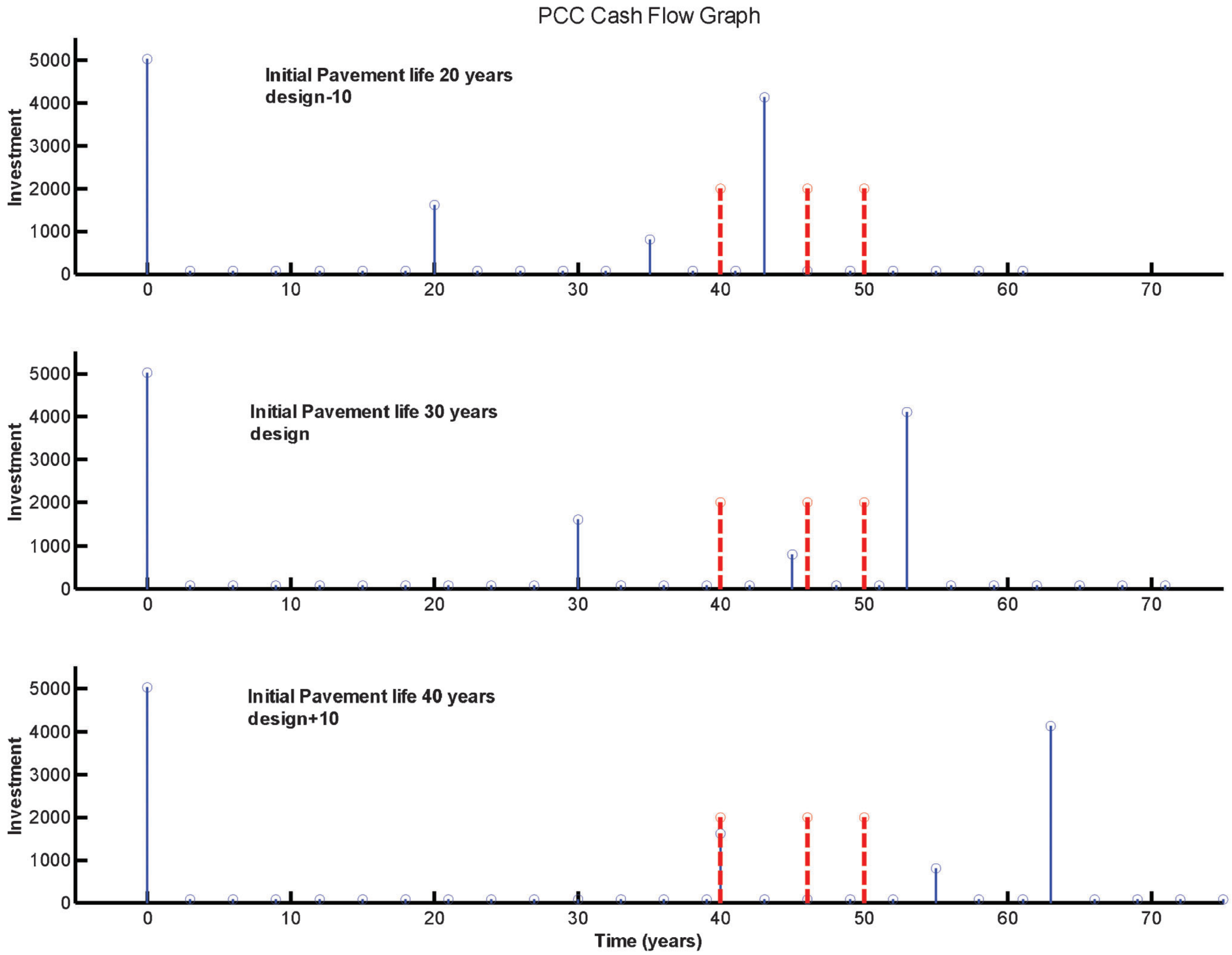

Figure 2.20 PCC Case 1 cash flow: red vertical lines LCCA evaluation periods.

TABLE 2.14
LCCA Analysis Results for 40-year Evaluation Period for HMA

Observed Pavement Life (years)	LCCA Case 2 Costs ($1,000)	LCCA Case 3 Costs ($1,000)	Pavement Life Observed/ Designed	Case 2 Costs Observed/ Designed	Case 3 Costs Observed/ Designed
10	$6,486.07	$5,918.32	0.5	1.20	1.10
12	$6,177.83	$5,773.80	0.6	1.14	1.08
14	$5,932.94	$5,670.57	0.7	1.10	1.06
16	$5,714.12	$5,571.19	0.8	1.06	1.04
18	$5,521.80	$5,454.61	0.9	1.02	1.02
20	$5,415.32	$5,367.32	1	1	1
22	$5,311.83	$5,283.04	1.1	0.98	0.98
24	$5,198.15	$5,188.55	1.2	0.96	0.97
26	$5,123.88	$5,123.88	1.3	0.95	0.95
28	$5,039.46	$5,039.46	1.4	0.93	0.94
30	$4,949.53	$4,949.53	1.5	0.91	0.92

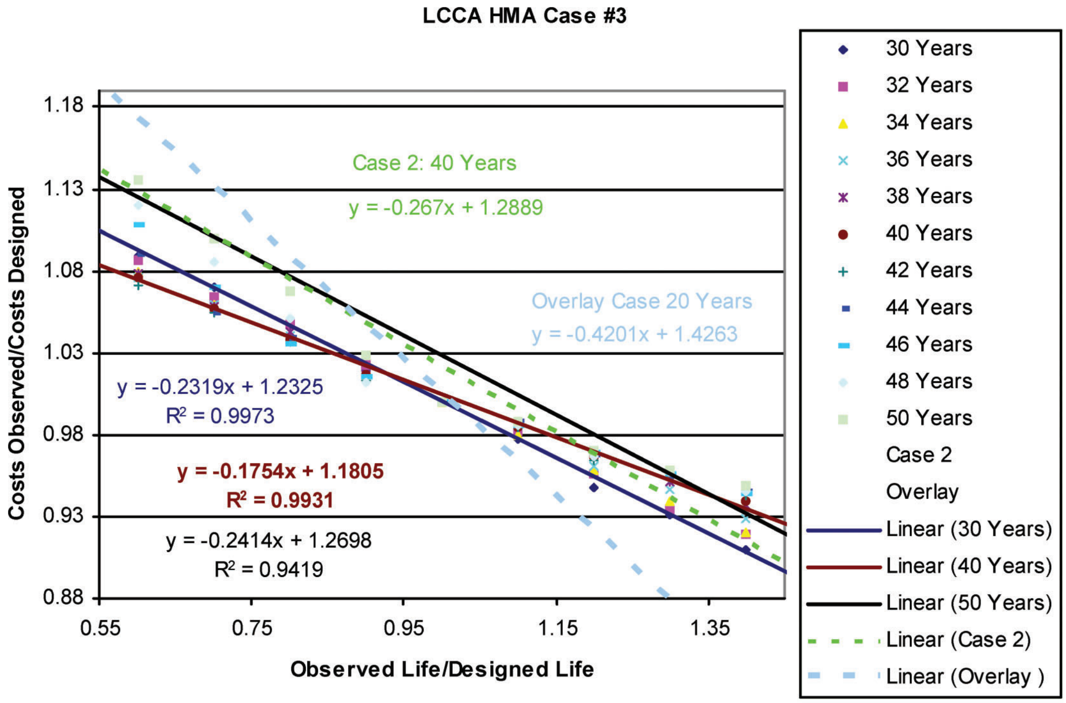

Figure 2.21 HMA Case 3 LCCA linear cost models: model selected (40 years).

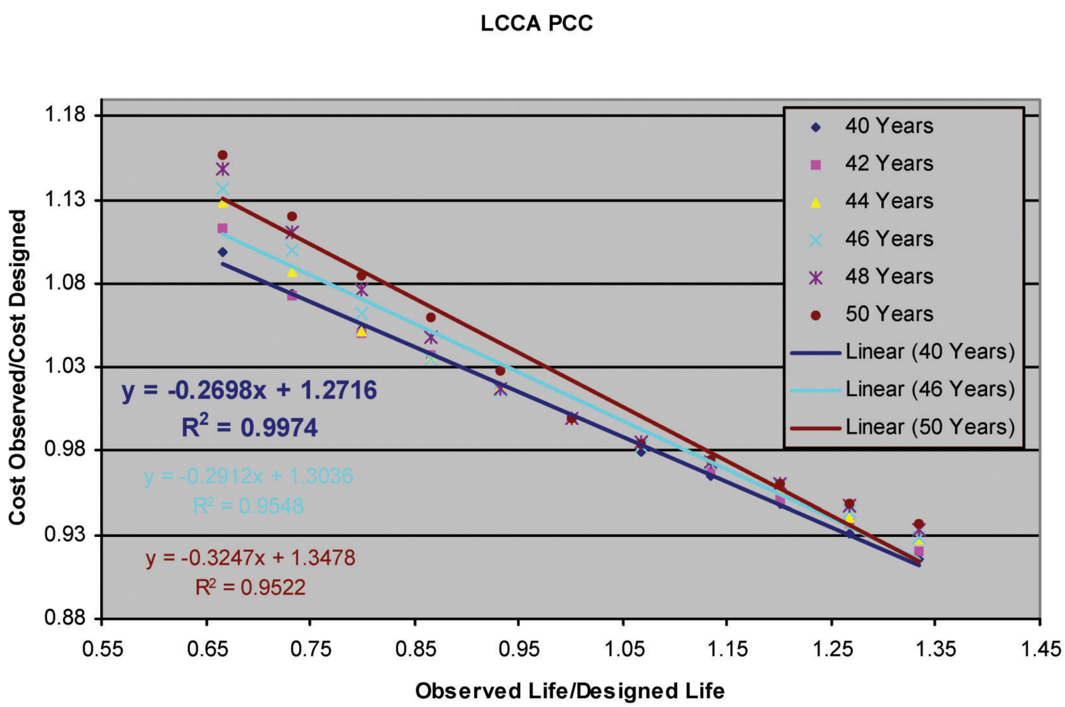

Figure 2.22 PCC Case 1 LCCA linear cost models: model selected (40 years).

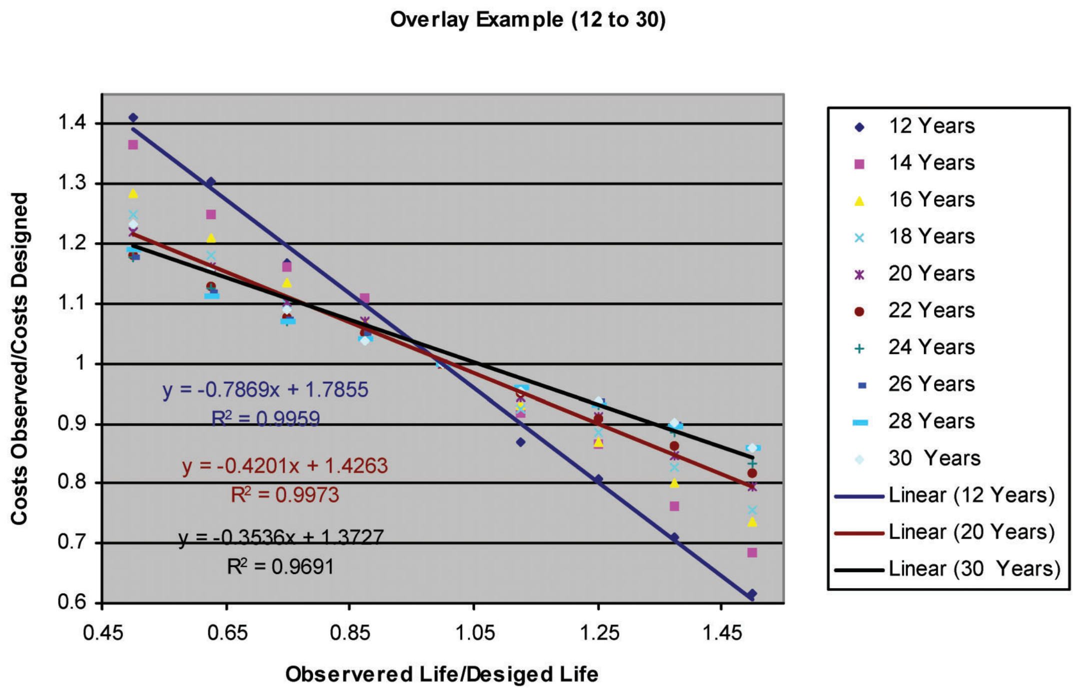

Figure 2.23 HMA overlay 1 LCCA linear cost models.

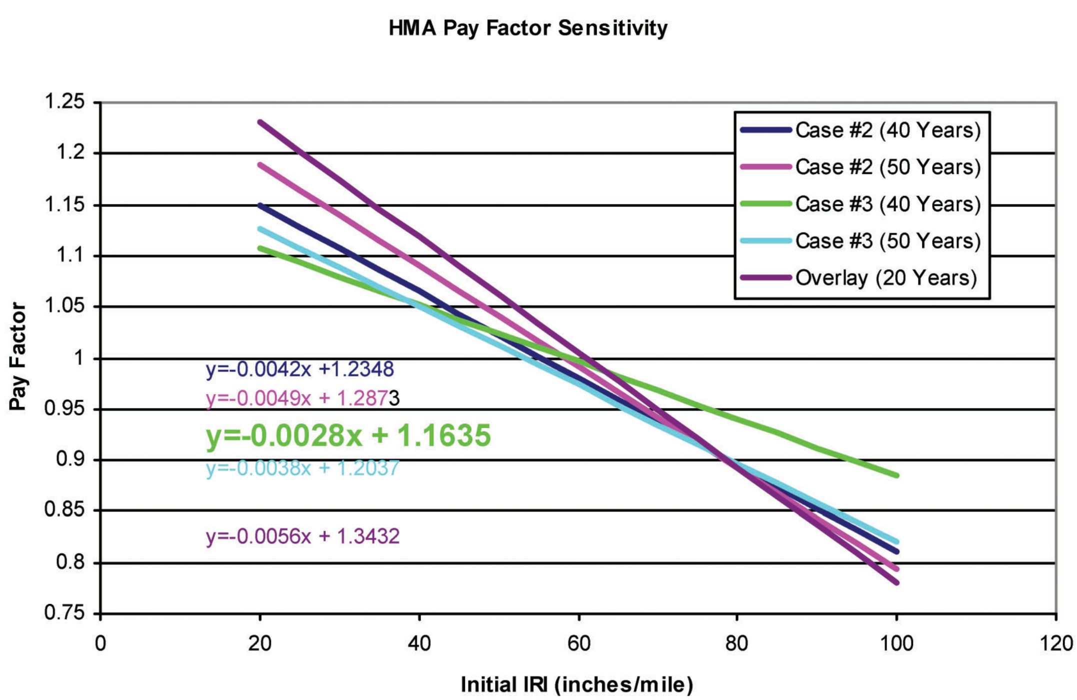

Figure 2.24 Pay factor sensitivity to LCCA parameters for HMA cases.

$$
\begin{aligned}
y &= -0.1754x + 1.1805 \\
x &= \text{observedpavementlife} \\
&\quad /\text{designedpavementlife} \\
y &= \text{costsatobservedpavement} \\
&\quad /\text{costsatdesignedpavementlife}
\end{aligned} \tag{7}
$$

The PCC model evaluated at 40 years was the model selected to be used for developing the PCC pay factor tables (see Equation 8):

$$
\begin{aligned}
y &= -0.2698x + 1.2716 \\
x &= \text{observedpavementlife} \\
&\quad /\text{designedpavementlife} \\
y &= \text{costsatobservedpavement} \\
&\quad /\text{costsatdesignedpavementlife}
\end{aligned} \tag{8}
$$

Pay factor models were developed for the HMA Overlay Case 1, HMA Case 2, HMA Case 3, and the PCC Case. Figure 2.24 is a plot of various pay factor models developed for HMA. The sensitivity of the pay factor models both the LCCA evaluation period and the rehabilitation strategy is evident. Using Case 2 (40 years) instead of Case 3 (40 years) for HMA pay factor tables would increase the smoothness bonus \$4,371 for every \$1M in material costs using HMA population or \$5,764 for every \$1M using HMA 2010 population.

2.6 Conclusions

Pay factor tables were developed for this study using a linear model that utilized an IRI life cycle model and LCCA. A multitude of very different pay factor tables could be generated with this modeling scheme using reasonable model inputs. The pay factor table values were very sensitive to the pavement rehabilitation plan. Furthermore the pay factor table values proved sensitive to the AADT, IRI threshold, and the duration of the LCCA analysis.

The proposed pay factor tables yield smoothness bonus values comparable to bonuses determined using the current specifications.

3. SMOOTHNESS QUALITY ASSURANCE INCENTIVE CALCULATION (SMOOTHNESS BONUS) METHODOLOGY ANALYSIS

The quality assurance incentive (smoothness bonus) for the proposed specification is calculated using the continuous IRI histograms determined using a 25 foot window size. For HMA pavements the smoothness bonus will be calculated using the following equation:

$$
\begin{aligned}
K &= 0.5 \times A \times \sum_{j=1}^{m} \frac{S_j}{T} \times U_j \\
Q_s &= K * \sum_{i=1}^{n} \left(PF_i^s - 1 \right) * (Z_i + Y_i) \\
Q_s &= \text{qualityassuranceadjustmentforsmoothness} \\
m &= \text{numberoflayers} \\
A &= \text{area(sqyd)} \\
S_j &= \text{Spreadrateformaterialoflayer}j\text{(lb/sqyd)} \\
U_j &= \text{unitpriceofmaterialforlayer}j\text{(\$/ton)} \\
T &= \text{conversionfactor2,000lb/ton} \\
PF_i^s &= \text{payfactorforsmoothnessforhistogramcell}i \\
Z_i &= \text{percentageofrightwheelpathIRIinhistogramcell}i \\
Y_i &= \text{percentageofleftwheelpathIRIinhistogramcell}i \\
n &= \text{numberofcells}
\end{aligned} \tag{9}
$$

For PCC pavements the smoothness bonus will be calculated using the following equation:

$$
\begin{aligned}
K &= 0.5 \times A \times U \\
Q_s &= K * \sum_{i=1}^{n} \left(PF_i^s - 1 \right) * (Z_i + Y_i) \\
Q_s &= \text{qualityassuranceadjustmentforsmoothness} \\
A &= \text{area(sqyd)} \\
U &= \text{unitpriceofmaterialformaterial(\$/sqyd)} \\
PF_i^s &= \text{payfactorforsmoothnessforhistogramcell}i \\
Z_i &= \text{percentageofrightwheelpathIRIinhistogramcell}i \\
Y_i &= \text{percentageofleftwheelpathIRIinhistogramcell}i \\
n &= \text{numberofcells}
\end{aligned} \tag{10}
$$

The fixed interval method and a histogram method utilizing the continuous IRI were the two methodologies selected as possible candidates for the specification. The fixed interval method involves splitting the road section being evaluated into lots of a specified length and then calculating the average IRI value to each of the lots. This average value is then assigned to the lot. The smoothness bonus is then calculated for each lot. The histogram method utilizes a histogram to assign the percentage of the continuous IRI values of the road section that falls into each of the cells of the pay factor table. The smoothness bonus is then calculated using these percentages.

The selection of the smoothness bonus calculation methodology proceeded in three steps. The first step in comparing the two methodologies was to analyze the IRI raw, continuous, and fixed interval populations. The second step was to calculate the smoothness bonuses for each of these methodologies for a number of test sites using the mean IRI (MRI), and the IRI of the individual wheel paths. The third step was to compare these results against each other and with the smoothness bonus results calculated using the current PI specification.

3.1 Population Analysis

HMA and PCC populations were assembled for this study for raw MRI values, continuous MRI values (25 foot window), and fixed interval MRI values (528 foot interval). ProVAL was used to perform the IRI filtering used to determine the values for all of these populations. The HMA 08/09 populations consist of 417 miles of IRI data collected on newly constructed HMA pavements between 2008 and 2009. A majority of the data was collected for smoothness awards; the remainder of the data was specifically collected for this study. The HMA 2010 populations, 223 miles, contains data collected in 2010. The PCC 2010 populations consist of 41 miles of IRI data collected on newly constructed PCC pavements in 2010. IRI data collected in 2010 was collected using RoLine line lasers, and IRI data collected in earlier years was collected using dot lasers. There is higher variability in IRI data collected on PCC pavement using dot lasers; consequently, data collected in early years is not presented here.

The MRI populations were created by running the individual road section profiles through the ProVAL IRI filter and exporting the data for each wheel path. The absolute values of the data files from the exported IRI values for the two wheel paths were then averaged. The averaged values for each road section (MRI) were combined to form the populations. The continuous MRI data populations were created by running the individual road section profiles through the ProVAL continuous IRI filter using a 25 foot window. The exported values for the left and right wheel paths were averaged (continuous MRI). The MRI values for each road section were then combined to form the populations. The fixed interval MRI populations were created by segmenting the MRI output for each road section into 528 foot lots. An average value was then calculated for each segment. These average values for each road section were combined to form the interval MRI population.

This histogram plots show the populations are not normally distributed (see Figure 3.1, Figure 3.2, and Figure 3.3). The populations are skewed to the right (positively skewed). There is a much higher likelihood of having a random rough event than a random smooth event. These rough events form the tail to the right.

The continuous IRI filter uses a moving average filter to smooth the raw MRI data. This smoothing filter collapses the histogram some (reduces the standard deviation). Since the MRI population is skewed to the right the tail pulls the histogram of the continuous IRI to the right, the mode of the moves to the right (see Figure 3.1, Figure 3.2, and Figure 3.3).

This collapsing of the histogram and modes movement to the right is even more pronounced in the fixed interval histogram especially in the PCC population (see Figure 3.1, Figure 3.2, and Figure 3.3). This movement of the histograms to the right means the

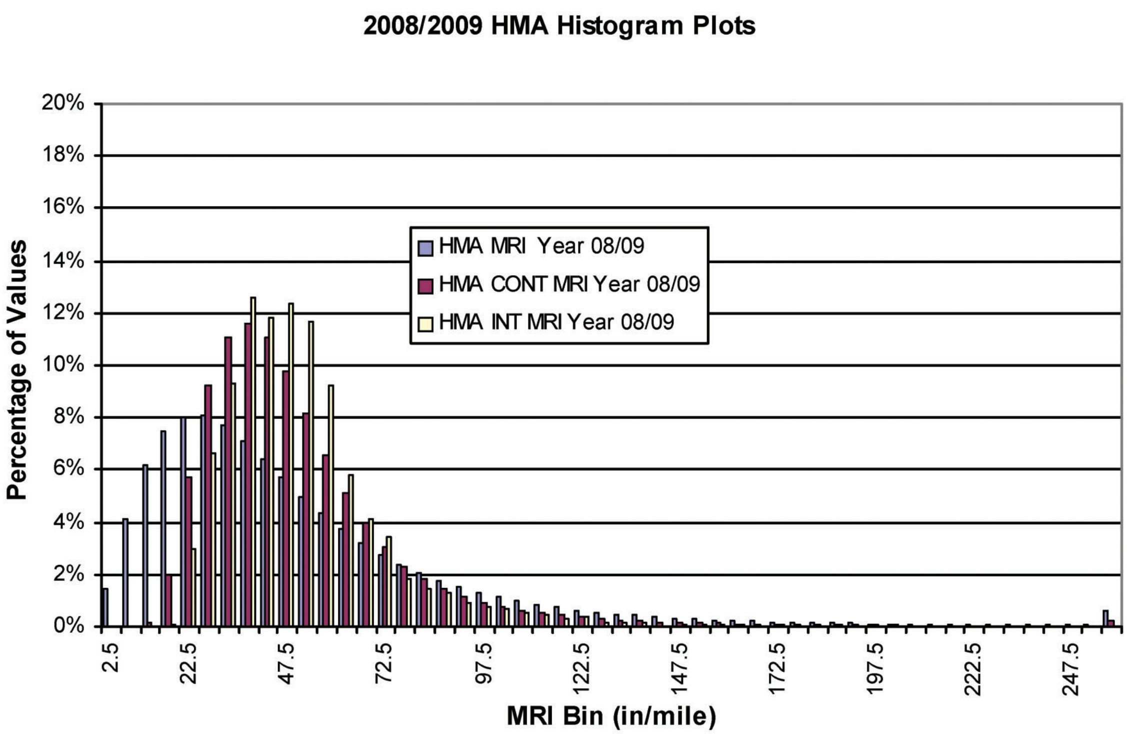

Figure 3.1 Histogram for the 2008/2009 HMA populations.

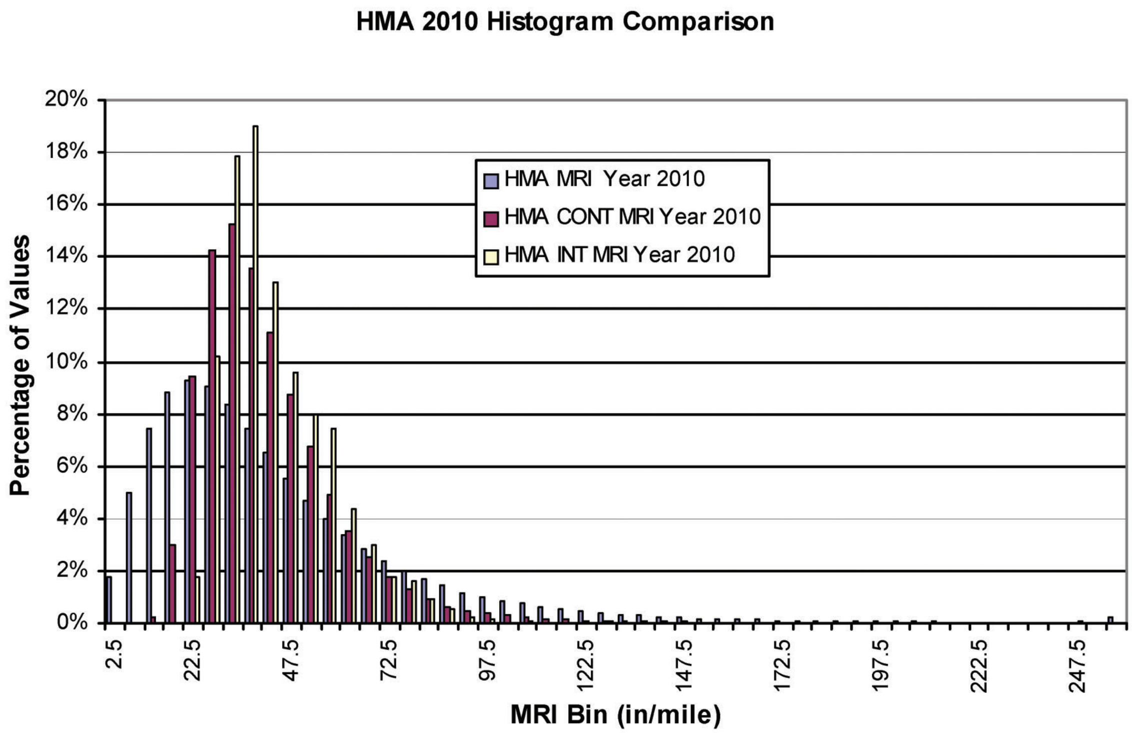

Figure 3.2 Histogram for the 2010 HMA populations.

smoothest values of the pavement do not contribute as much to a smoothness bonus calculated using the fixed interval population as opposed to one calculated using the continuous IRI population. There are much fewer values to the left of and including the hatched horizontal column is much for the fixed interval MRI populations as opposed to the continuous MRI populations (see Figure 3.4 and Figure 3.5).

The difference between the continuous MRI and the interval MRI populations is also clearly visible in the

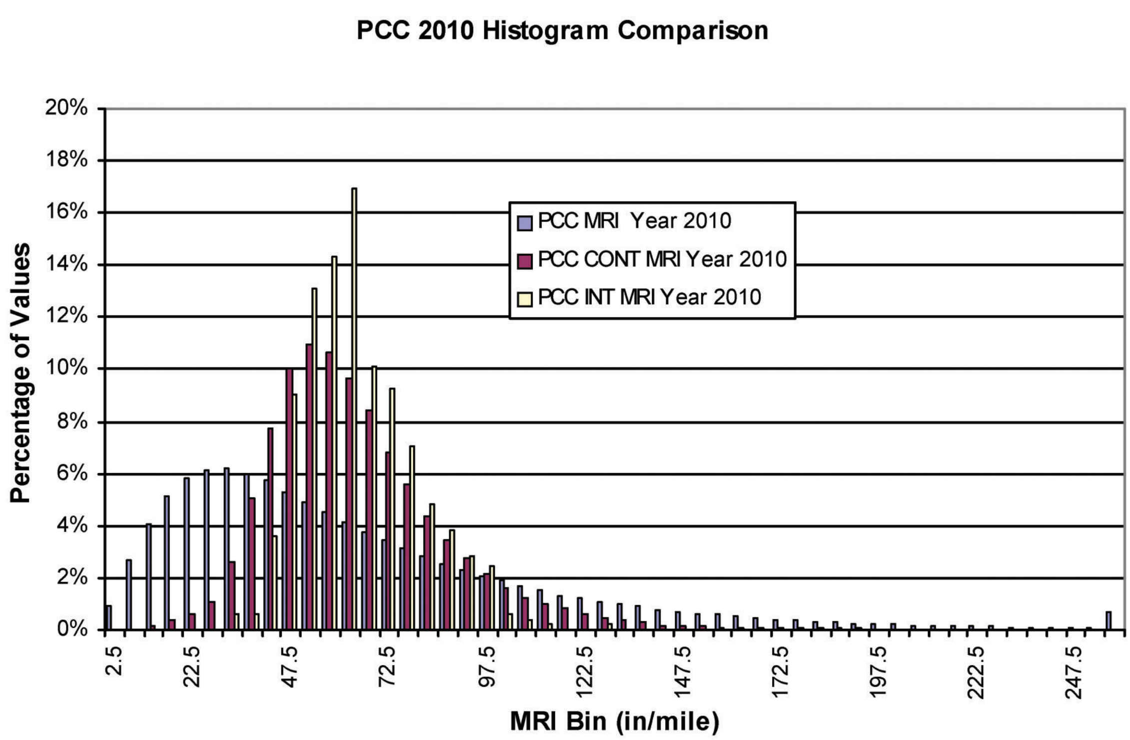

Figure 3.3 Histogram for the 2010 PCC populations.

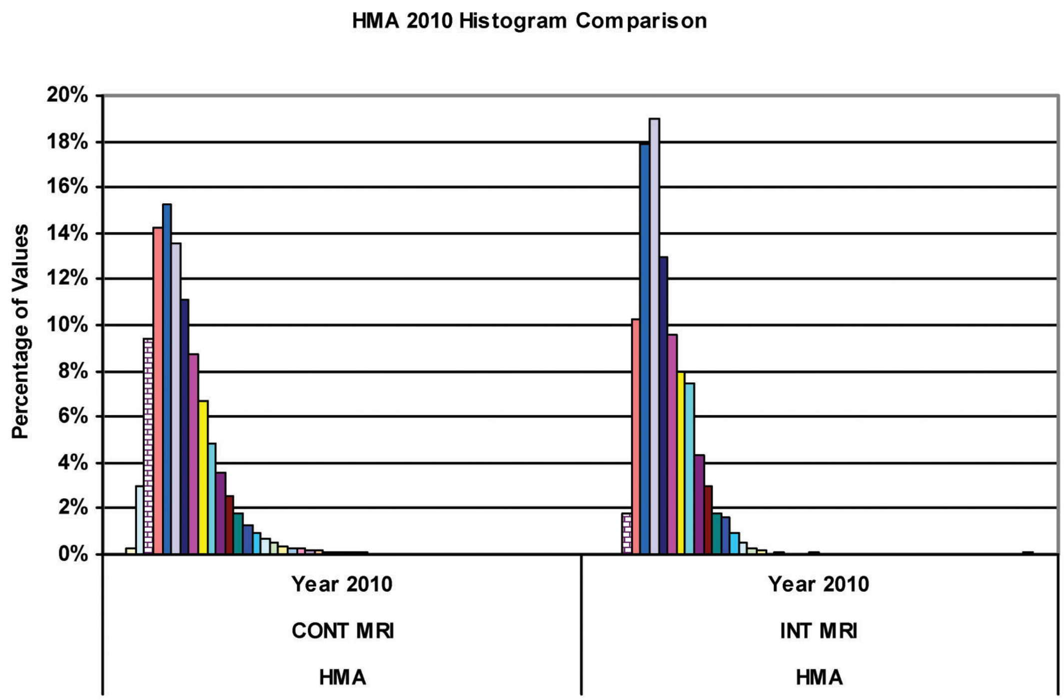

Figure 3.4 Histogram comparison of the HMA populations.

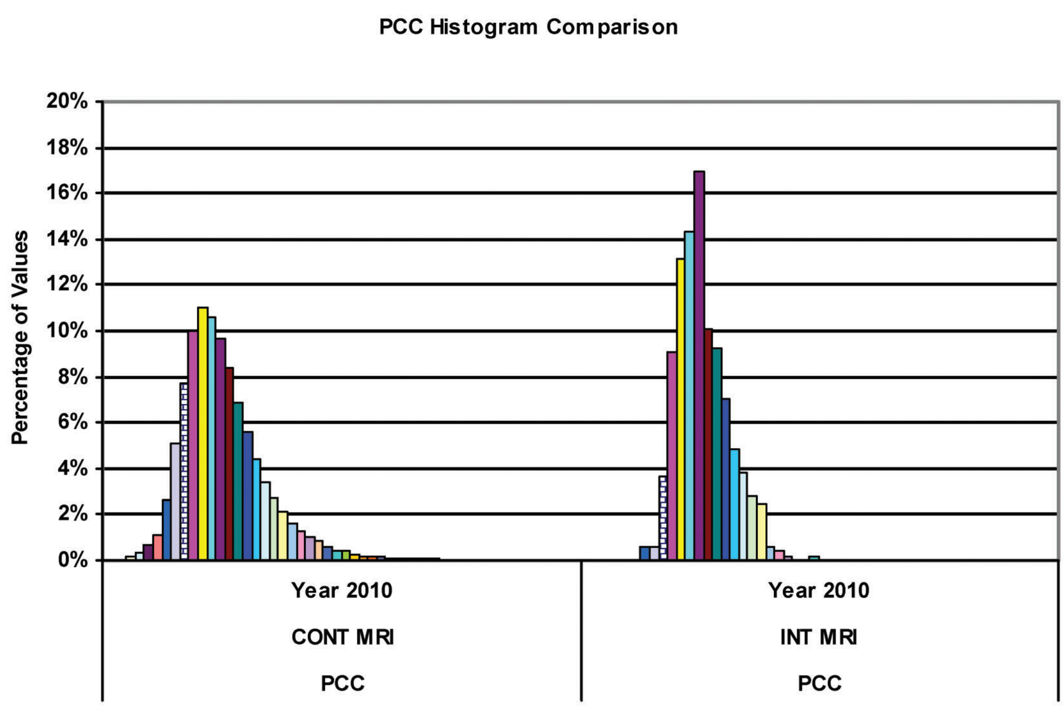

Figure 3.5 Histogram comparison of the PCC populations.

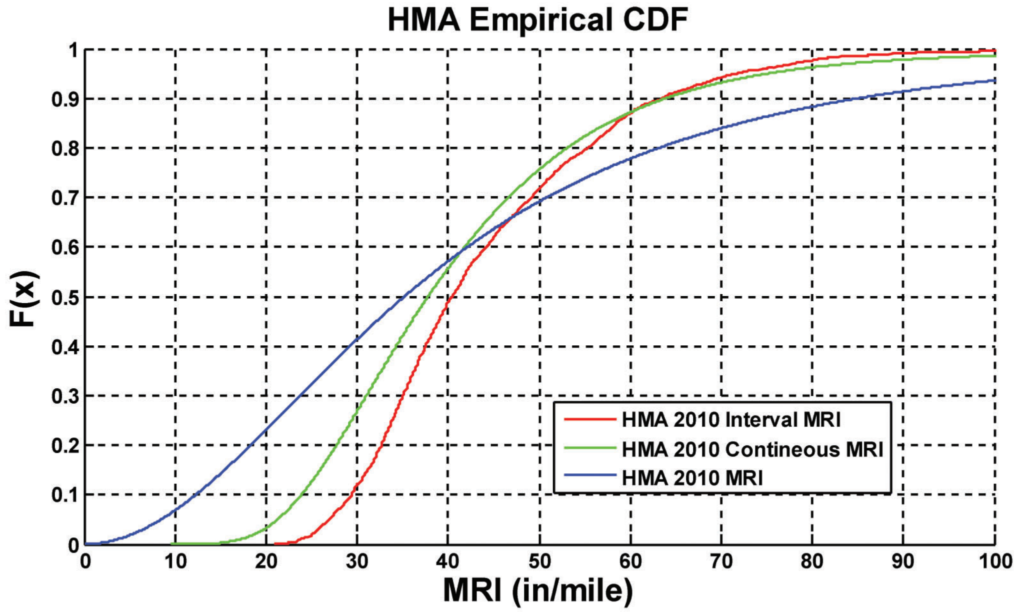

Figure 3.6 Cumulative distribution plot of the 2010 HMA populations.

cumulative distribution plots of the populations (see Figure 3.6 and Figure 3.7).

The cumulative distribution plots of the PCC populations show that approximately 2% of the interval MRI population and 10% of the continuous MRI population are have values less than or equal to 40 inches per mile. However, approximately 38% of the MRI population has values less than or equal to 40 inches per mile (see Figure 3.7).

Descriptive statistics for the MRI populations are found in Table 3.1. Descriptive statistics for the continuous MRI populations are found in Table 3.2. Descriptive statistics for the fixed interval MRI populations are found in Table 3.3. There is little difference in the means for the 2010 HMA populations, the 2008/2009 HMA populations, the 2010 PCC populations or the 2008/2009 PCC populations. However there is significant difference in the standard

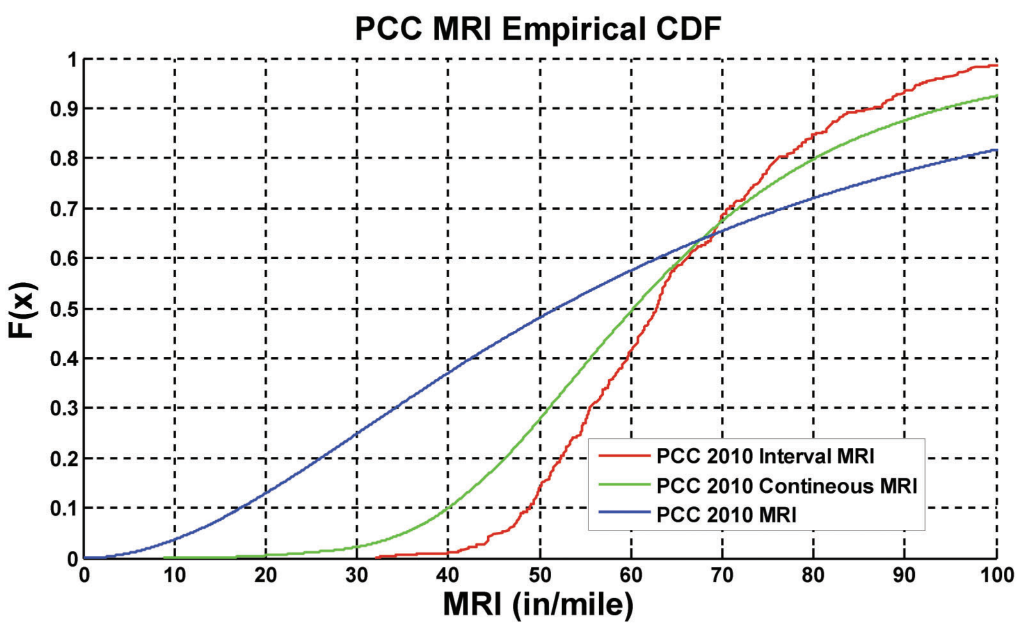

Figure 3.7 Cumulative distribution plot of the 2010 PCC populations.

TABLE 3.1
MRI Population Descriptive Statistics

	MRI (in/mile) HMA 2010	MRI (in/mile) HMA 2008/2009	MRI (in/mile) PCC 2010	MRI (in/mile) PCC 2008/2009
N	5,503,126	11,102,923	1,020,747	684,180
Mean	44.22	51.22	64.78	76.67
Standard Deviation	37.14	46.06	50.20	60.58
Minimum	0.02	0.01	0.06	0.08
Maximum	2732.81	3235.24	1552.88	1957.21
Median	35.24	39.95	51.99	61.74
Mode	22	24	32	40
Geometric Mean	33.42	37.99	48.77	58.16
Trimmed Mean 10%	40.30	46.02	59.86	70.53
Trimmed Mean 20%	38.71	44.08	57.54	67.87
Interquartile Range	35.34	40.95	55.23	63.11
Median Absolute Deviation	16.45	19.00	25.50	29.35
Mean Absolute Deviation	24.72	29.57	36.51	42.59
Kurtosis	132.79	89.69	19.45	31.41
Skewness	5.31	5.10	2.38	3.06

deviations for the same populations. The standard deviations of the continuous MRI populations are significantly lower than those of the MRI populations (see Table 3.1 and Table 3.2).

Furthermore, the standard deviations of the fixed interval MRI populations are significantly lower than the standard deviations of the continuous MRI populations. This result is expected because the use of the moving average filter and the averaging process used to create the fixed interval populations smooth the data.

In order to determine if the results of these large populations were reflected in the smaller populations used in calculating the fixed interval MRI, a study was conducted on a number of these fixed interval populations. Each population is composed of the 2,112

TABLE 3.2
Continuous MRI Descriptive Statistics

	CONT MRI (in/mile) HMA 2010	CONT MRI (in/mile) HMA 2008/2009	CONT MRI (in/mile) PCC 2010	CONT MRI (in/mile) PCC 2008/2009
N	5,494,437	11,094,744	1,017,293	682,981
Mean	41.84	51.22	64.74	76.67
Standard Deviation	18.42	29.40	24.43	32.18
Minimum	9.62	8.34	8.84	18.96
Maximum	386.40	688.09	412.65	479.37
Median	37.78	44.66	60.36	69.29
Mode	31	37	54	59
Geometric Mean	38.65	45.77	60.78	71.39
Trimmed Mean 10%	40.15	47.92	62.94	73.74
Trimmed Mean 20%	39.45	46.78	62.15	72.44
Interquartile Range	20.27	26.13	26.93	34.64
Median Absolute Deviation	9.63	12.49	12.99	16.28
Mean Absolute Deviation	13.32	19.01	17.77	23.16
Kurtosis	13.45	32.96	11.92	13.81
Skewness	2.16	3.75	1.86	2.23

TABLE 3.3
Fixed Interval MRI Descriptive Statistics

	INT MRI HMA 2010	INT MRI HMA 2008/2009	INT MRI PCC 2010	INT MRI PCC 2008/2009
N	2622	5295	496	330
Mean	44.33	51.26	64.97	76.78
STD	15.72	21.17	14.48	20.52
Min	21.00	19.48	32.19	41.49
Max	248.46	259.68	127.90	152.21
Median	40.44	47.64	62.86	71.06
Mode	34	44	63	57
Geometric Mean	42.19	47.83	63.44	74.32
Trimmed Mean 10	43.05	49.20	64.35	75.57
Trimmed Mean 20	42.46	48.46	63.85	74.46
Interquartile Range	17.94	21.51	19.41	25.97
Median Absolute Deviation	8.13	10.71	9.73	11.71
Mean Absolute Deviation	11.39	14.81	11.53	16.46
Kurtosis	28.97	11.54	3.52	3.46
Skewness	3.03	2.13	0.72	0.98

samples, the approximate number of samples in 528 feet. Examples from smooth and rougher HMA and PCC pavement sections were examined.

The first example is a smooth HMA pavement lot from a section of road on US-50. The fixed interval MRI value is less than 30 inches per mile (see Figure 3.8). A plot of the raw IRI values for this lot is included (see Figure 3.9). The histogram and QQ plot of this population show that the population is skewed to the right (see Figure 3.10 and Figure 3.11).

A rougher lot from the same pavement sections with a MRI of 60 in/mile shows a much more pronounced

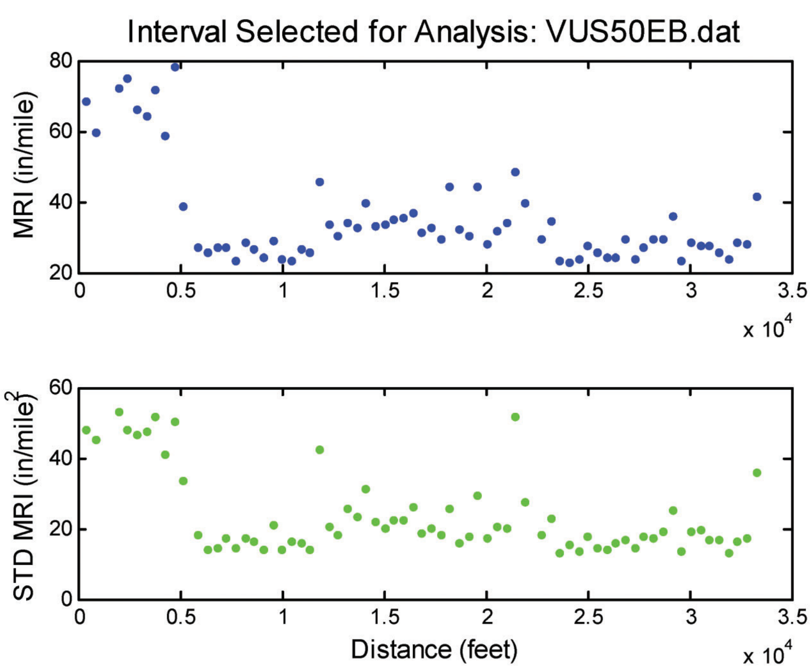

Figure 3.8 HMA US-50 interval MRI and standard deviation; red X = sample.

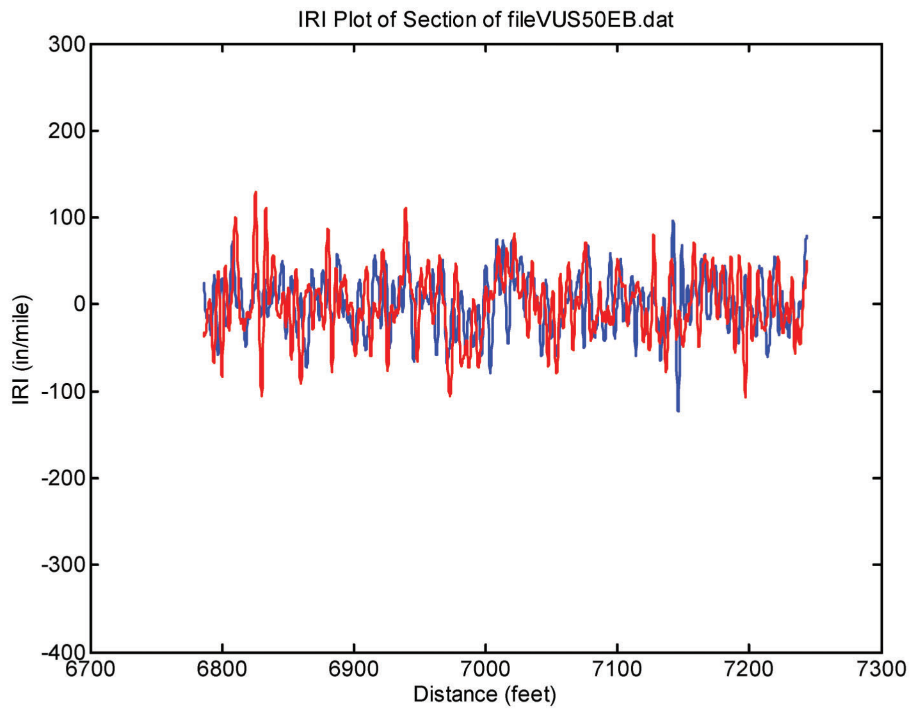

Figure 3.9 HMA US-50 IRI values for selected lot.

tail. The location of the sample selected is included in Figure 3.12 (see Figure 3.12). The IRI values have more variability than the previous example (see Figure 3.9 and Figure 3.13). The histograms and QQ plots indicates the population has a more prominent skew to the right than the previous population (see Figure 3.10, Figure 3.11, Figure 3.14, and Figure 3.15).

A smooth PCC pavement example from US-24 with an average MRI of about 50 inches per mile (see Figure 3.16 and Figure 3.17) has a positive skew and tail to the right that is evident in the histogram and QQ-plot (see Figure 3.18 and Figure 3.19).

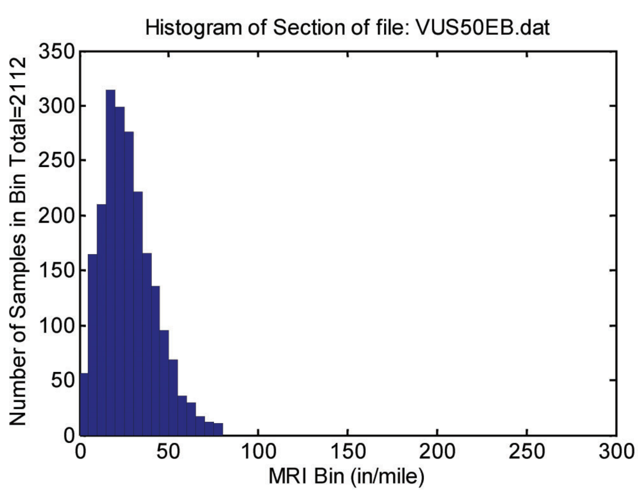

Figure 3.10 Histogram of population of selected HMA lot US-50.

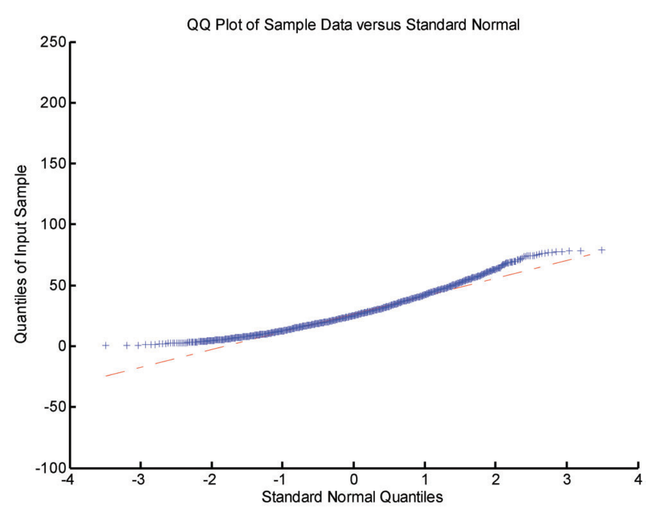

Figure 3.11 QQ plot of population of selected HMA lot US-50.

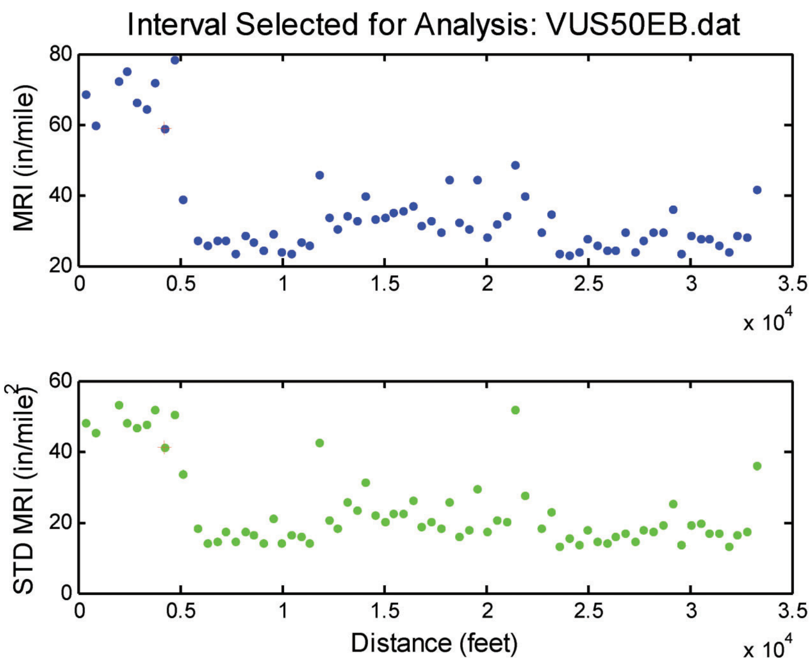

Figure 3.12 HMA US-50 interval MRI and standard deviation; red X = sample.

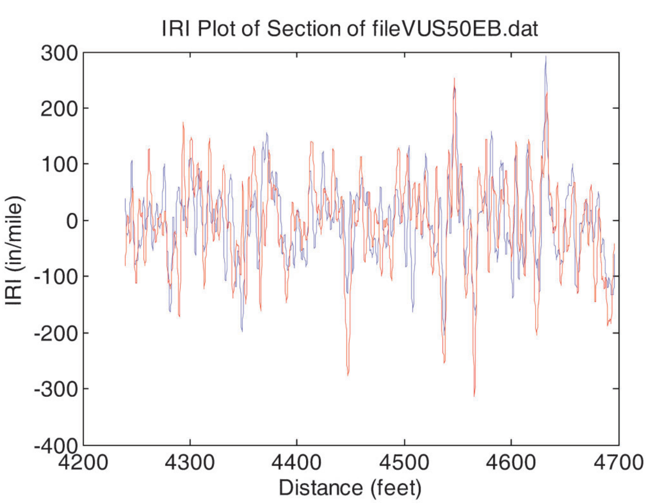

Figure 3.13 HMA US-50 IRI values for selected lot.

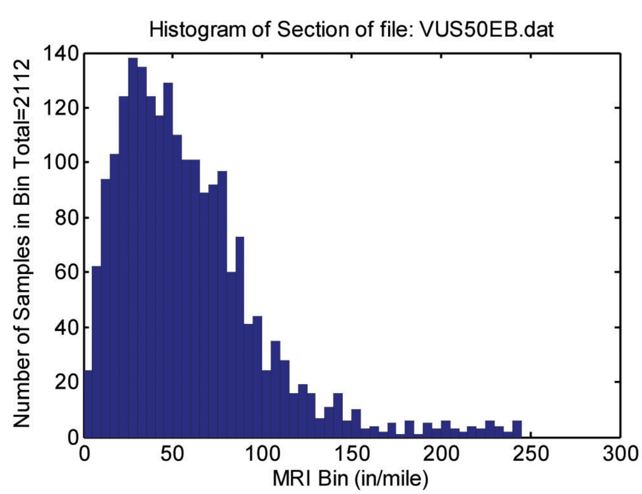

Figure 3.14 Histogram of population of selected HMA lot US-50.

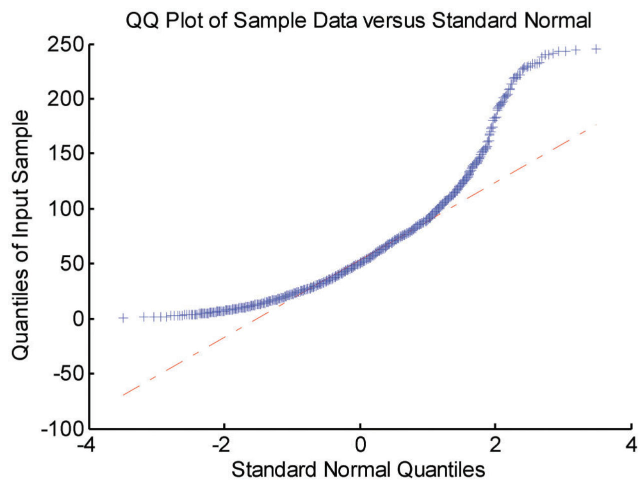

Figure 3.15 QQ plot of population of selected HMA lot US-50.

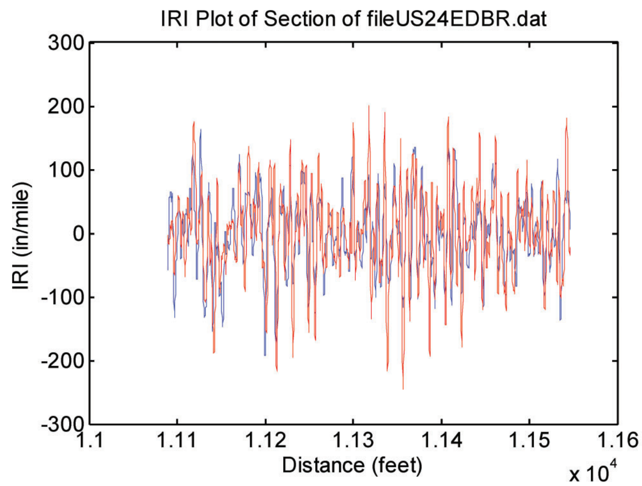

Figure 3.17 PCC US-24 IRI values for selected lot.

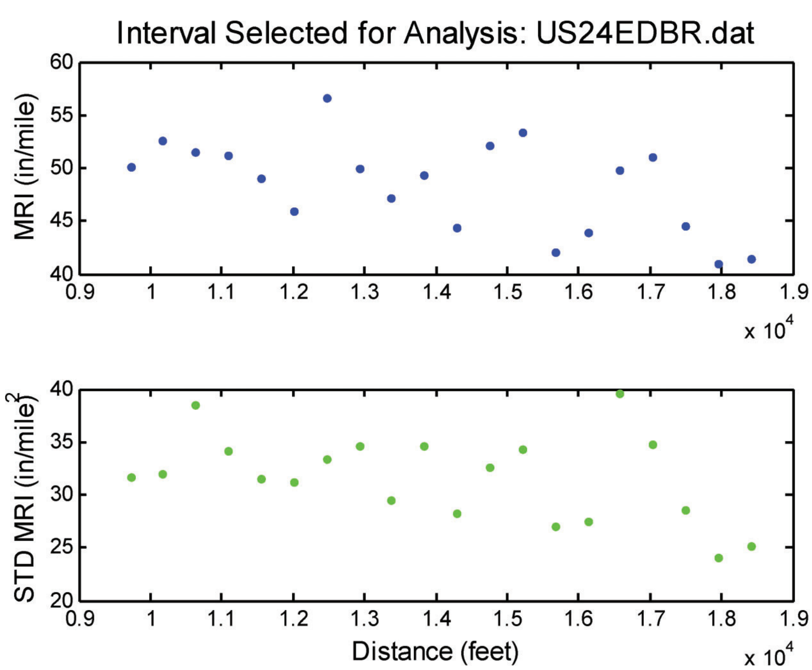

Figure 3.16 PCC US-24 interval MRI and standard deviation; red X = sample.

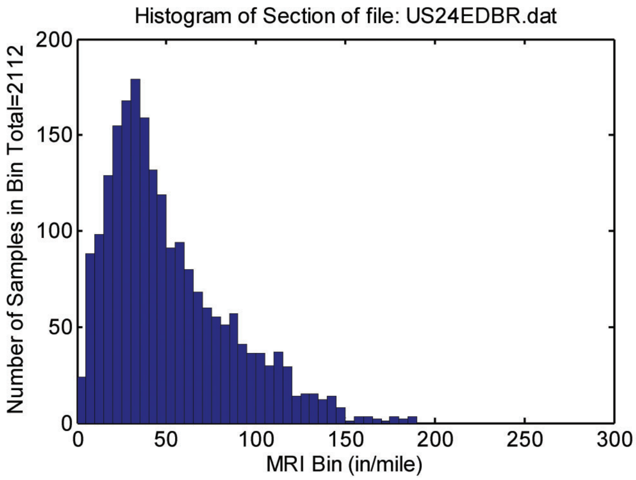

Figure 3.18 Histogram of population of selected PCC lot of US-24.

An example of PCC pavement with an average MRI of about 70 inches from US-20 (see Figure 3.20) has a very pronounced positive skew and tail that is evident in the histogram and QQ-plots (see Figure 3.21 and Figure 3.22). The tail is more prevalent than that of the smoother PCC pavement example (Figure 3.18, Figure 3.19, Figure 3.21, and Figure 3.22). Notice that the population does contain a fair portion of smoothness values less than 50 in/mile; however, the average for the lot is 70 in/mile consequently, there would be no bonus paid for this lot.

3.1.1 Population Conclusions

The population study showed that the MRI populations are not normally distributed, but are skewed to the right; therefore, there is significant difference between mode and mean of the populations. The tail

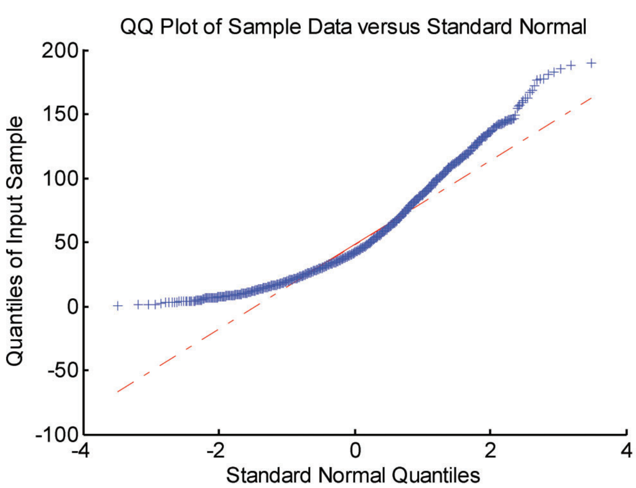

Figure 3.19 QQ plot of population of selected PCC lot of US-24.

of the MRI populations reflects the smoothness irregularities present in the pavement. These smoothness irregularities have a pronounced impact on the fixed interval and continuous MRI populations and the calculated smoothness incentives. The positive skew characteristics were also present in the smaller MRI populations utilized for calculating the fixed interval MRI.

More than 82% of the 2010 HMA continuous MRI population is eligible for a smoothness incentive, and more the 55% of the population qualified for the biggest pay factor (1.06) (see Table 3.4). These numbers decrease to more than 79% and 48% respectively for the 2010 HMA fixed interval populations. Less than 39% of the 2010 PCC continuous MRI population qualified for a smoothness incentive, while less than 5% qualified for the biggest pay factor. These numbers decrease to less than 28% and 1% respectively for the 2010 PCC fixed interval populations.

The percentage of the HMA populations that qualify for the biggest pay factor (1.06) is large; however, the calculated incentive was reasonably close to incentives calculated using the current specification for many pavement sections (see section 2.3, Smoothness Bonus Comparison).

Only 67.3% of PCC continuous MRI population met the100% smoothness pay criteria compared 93.15% of the HMA continuous MRI population. There were instances where the proposed specification paid out much more than the current specification and cases where the proposed specification paid out much less (see section 2.3, Smoothness Bonus Comparison, and Table 2.10).

3.2 Methodology Comparisons

A comparison of methodologies was conducted to contrast the smoothness incentives calculated using the fixed interval and smoothness histogram methodologies and to evaluate differences between incentives calculated using IRI of the individual wheel paths verses those calculated using MRI. The histogram methodology penalizes for all of the values above 70 in/mile where intervals above 90 in/mile were not included in the penalization of the fixed interval incentive.

The calculated smoothness incentives for twenty seven sections newly constructed HMA pavement sections were examined to evaluate differences in incentives calculated using the proposed histogram methodology and the fixed interval methodology. The histogram methodology paid out less incentive than the fixed interval methodology in 19 out of the 27 sections (70% of the sections) using MRI values, and 20 out of the 27 sections (75% of the sections) using IRI (see Figure 3.23). The difference in the incentives paid ranged from 0.3% to 35% where the larger differences are associated with rougher pavements (see Figure 3.23). 100% of the pavement sections with an average MRI of less than 49 inches per mile had differences of 10% or less.

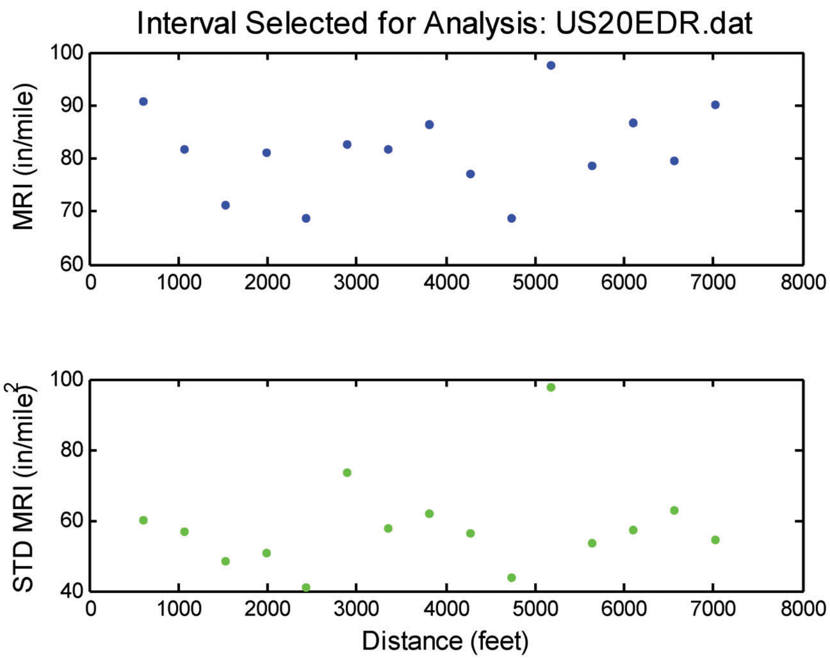

Figure 3.20 PCC US-20 interval MRI and standard deviation; red X = sample.

The same 27 sections were examined to evaluate differences in the smoothness incentives calculated using MRI and IRI. When this IRI method is utilized the pavement section is split in two with half the incentive calculated using the IRI of the right wheel path and half the incentive calculated using the left wheel path. When using the MRI methodology the smoothness incentive is calculated from the average of the two IRI profiles (MRI).

As shown in Figure 3.24, the smoothness incentives for the MRI and IRI methodologies yielded results that were within 10% for a majority of the pavement sections. There was no difference between the MRI and IRI in some cases and there was as much as 6.8 percent difference for incentives calculated using the histogram methodology, and there was as much as 20.5% difference in incentives calculated using the fixed interval methodology.

The smoothness incentives calculated using the methodologies presented here were also compared to the smoothness incentives calculated using the current specification (2008 PI) for these 27 HMA pavement sections. As shown in Figure 3.25, the results are similar for 12 of the 27 pavement sections; however,

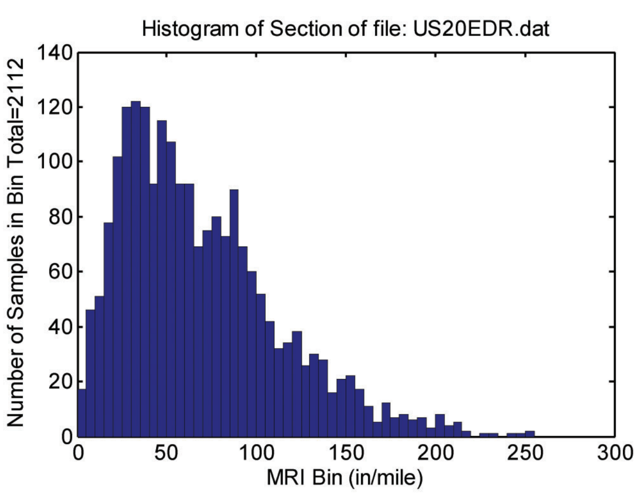

Figure 3.21 Histogram of population of selected PCC lot of US-20.

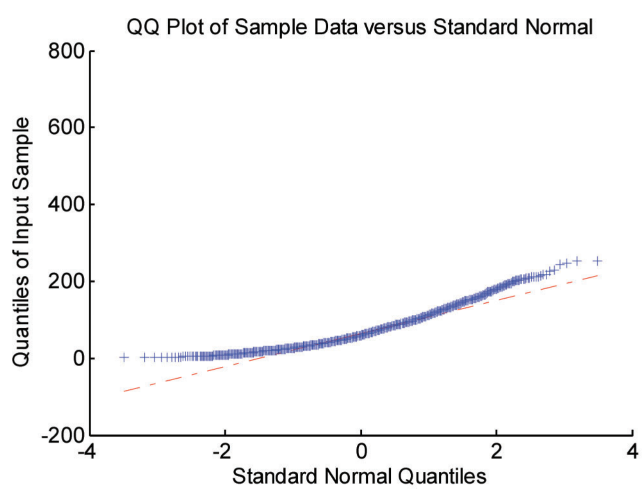

Figure 3.22 QQ plot of population of selected PCC lot of US-20.

TABLE 3.4
Population Pay Factor Table Results

	MRI Threshold (in/mile)	HMA MRI	HMA CONT MRI	HMA INT MRI	PCC MRI	PCC CONT MRI	PCC INT MRI
				2010			
Highest Pay Factor	X ≤ 35	49.62%	42.09%	29.90%	30.95%	4.83%	0.60%
Pay Factor at least 1.06	X ≤ 40	57.06%	55.68%	48.89%	36.94%	9.91%	1.21%
Pay Factor >1	X ≤ 55	73.78%	82.22%	79.44%	52.90%	38.65%	27.02%
100% Pay	55 < X ≤ 70	10.14%	10.93%	14.76%	12.48%	28.68%	41.33%
Penalization	70 < X ≤ 90	7.47%	4.63%	4.92%	11.92%	20.23%	25.00%
Corrective Action	X > 90	8.61%	2.22%	0.88%	22.69%	12.44%	6.65%
				2008/2009			
Highest Pay Factor	X ≤ 35	42.97%	28.09%	19.09%	23.40%	1.39%	0.00%
Pay Factor at least 1.06	X ≤ 40	50.07%	39.67%	31.67%	28.64%	4.08%	0.00%
Pay Factor >1	X ≤ 55	67.17%	68.71%	67.59%	43.81%	24.60%	7.58%
100% Pay	55 < X ≤ 70	11.36%	15.60%	19.23%	13.05%	26.53%	39.70%
Penalization	70 < X ≤ 90	8.97%	8.56%	7.97%	13.21%	23.99%	29.09%
Corrective Action	X > 90	12.50%	7.13%	5.21%	29.92%	24.87%	23.64%

there are instances where the calculated incentives are much larger or smaller. The smoothness incentives calculated using the current specifications are not penalized for pavement above the remediation level. This may be one of the reasons for the differences for the rougher pavements. The current specification converted IRI shows a much wider 100% band and a specification much more forgiving to rough pavements (see Figure 2.5 and Figure 2.6). Furthermore, the difference between using the proposed specification and the current specification presented in section 2.1 Pay Factor Table Conversion.

The calculated smoothness incentives for eighteen sections newly constructed PCC were examined to evaluate differences in incentives calculated using the proposed histogram methodology and the fixed interval methodology. The relative difference was utilized for this evaluation because there were instances where there was a mix of incentives and penalization (negative incentive values). There was significant differences between the smoothness incentives calculated using the histogram method and those calculated using the fixed interval methodology (see Figure 3.26). The large increase in the histogram smoothness incentives

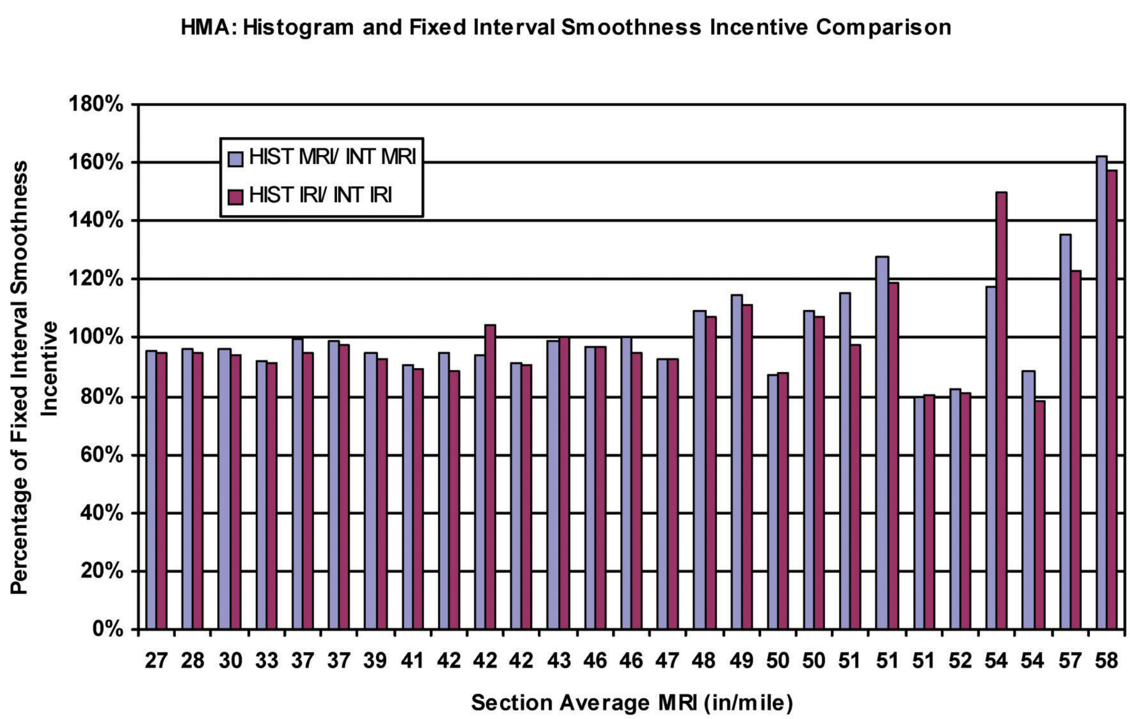

Figure 3.23 HMA: histogram and fixed interval smoothness incentive comparison.

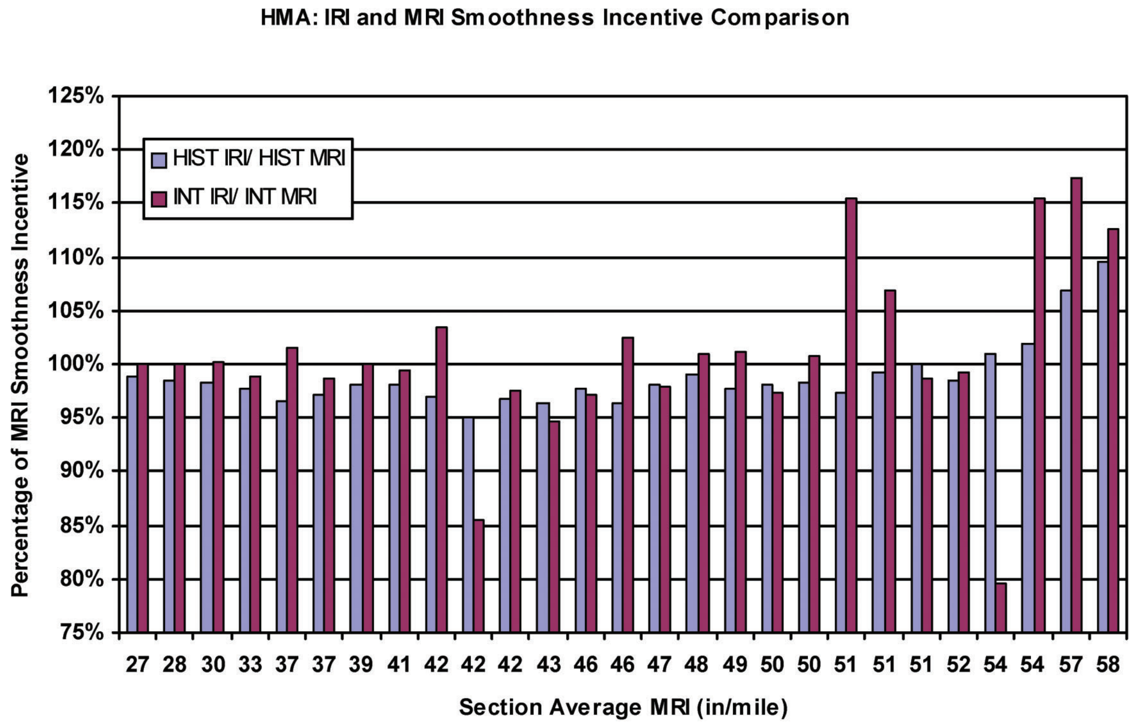

Figure 3.24 HMA: IRI and MRI smoothness incentive comparison.

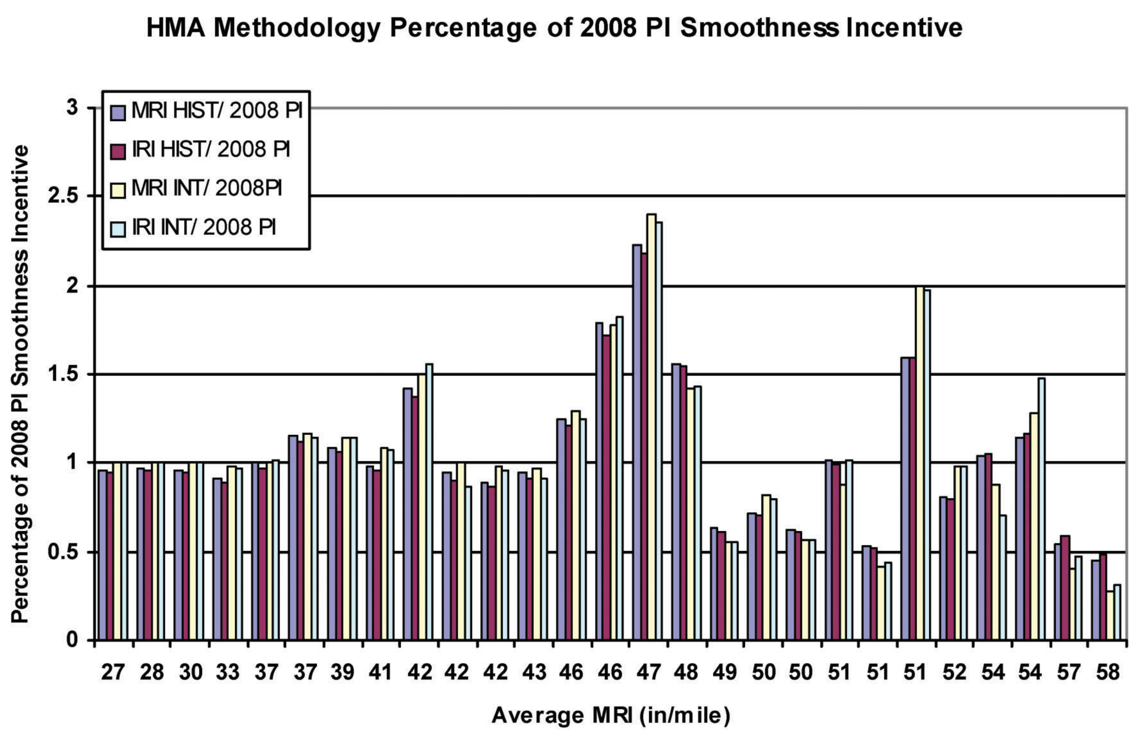

Figure 3.25 Smoothness incentive comparison results.

compared to the fixed interval (fixed interval population) is due to the fact that the smooth areas have a larger influence for the histogram method (continuous MRI population) due the properties of the populations and the effect of the positive skew (see Figure 3.3). This is the case for the pavement sections with average MRI values between 52 and 74 in/mile and the pavement section with 82 in/mile (see Figure 3.26). The effect of the positive skew is also evident in the histograms of the individual pavement sections. For the pavement sections with an average MRI of 67, and 66 in/mile (see Figure 3.26), there are higher percentages of the smoothness values less than 40 in/mile in the continuous population than there are in the fixed interval population (see Figure 3.27, Figure 3.28, Figure 3.29, and Figure 3.30). The large increase in the fixed interval incentives as compared to the histogram incentives is due to the fact that there is no penalization for lots with IRI values above 90 in/mile for incentives calculated using the fixed interval methodologies (see Figure 3.26). This is the case for the pavements sections with average MRI values of 77, 80, 84, and 87 in/mile (see Figure 3.26).

The same 18 sections were examined to evaluate differences in the smoothness incentives calculated using MRI and IRI. There were noticeable differences between the smoothness incentive calculated using the IRI verses those calculated using MRI (see Figure 3.31 and Figure 3.32). This indicates a perceptible difference in the smoothness of the two wheel paths. The result in smoothness incentives depends on smoothness histograms placement on the pay factor table.

For the incentives calculated using the histogram method, the IRI incentive was always greater (see Figure 3.31). Histograms were examined for the individual pavement sections with average MRI of 67, and 84 in/mile to investigate the differences between incentives calculated using IRI and MRI. The IRI incentive for pavement section with an average MRI of 67 in/mile is significantly larger that the incentive calculated using MRI (see Figure 3.31). There are higher percentages of the individual IRI values in the cell less than 40 in/mile as apposed the MRI (see Figure 3.27). For the pavement section with an average MRI of 84 in/mile the percentages of the individual IRI values in the cells less than 40 in/mile are still larger; however, this does not offset the larger number of IRI values in cells above 90 in/mile especially the for IRI 1 (see Figure 3.33). Consequently, the relative difference is smaller (see Figure 3.31).

For incentives calculated using the fixed interval method, the IRI incentives were greater for approximately 44% of the sections (see Figure 3.32). Therefore, the MRI incentives were greater for 56% of the sections. The cause of the differences in incentives was not apparent in histograms plotted for the pavement sections average MRI of 63 in/mile and 66 in/mile (see Figure 3.30 and Figure 3.34).

3.3 Section Conclusions

The proposed smoothness specification utilizes the continuous IRI smoothness histograms of the individual wheel paths to calculate the smoothness quality

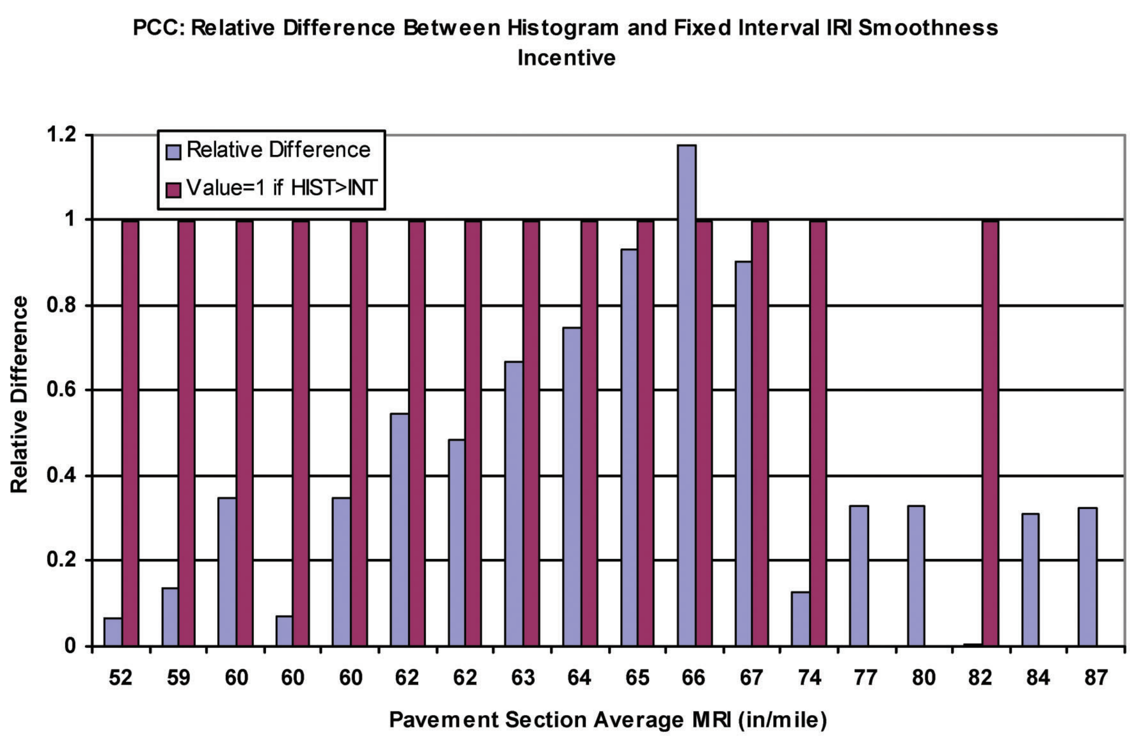

Figure 3.26 Relative difference between smoothness incentives calculated using the histogram methodology and the fixed interval methodology.

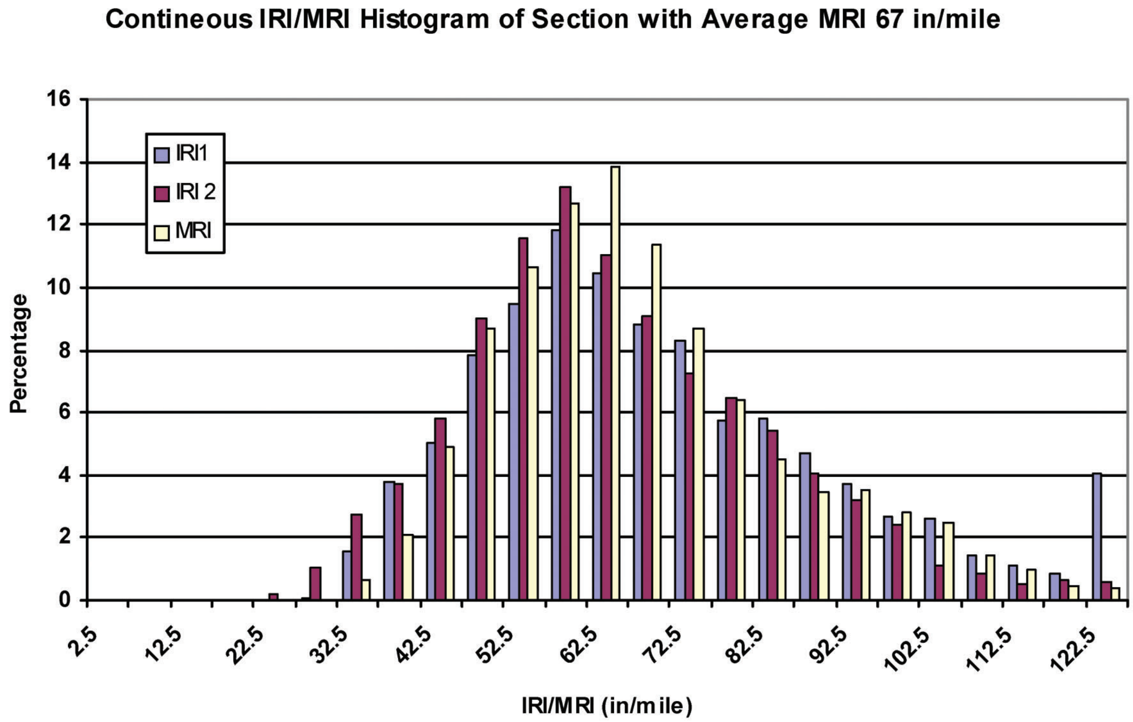

Figure 3.27 Histogram of continuous IRI and MRI values for pavement section.

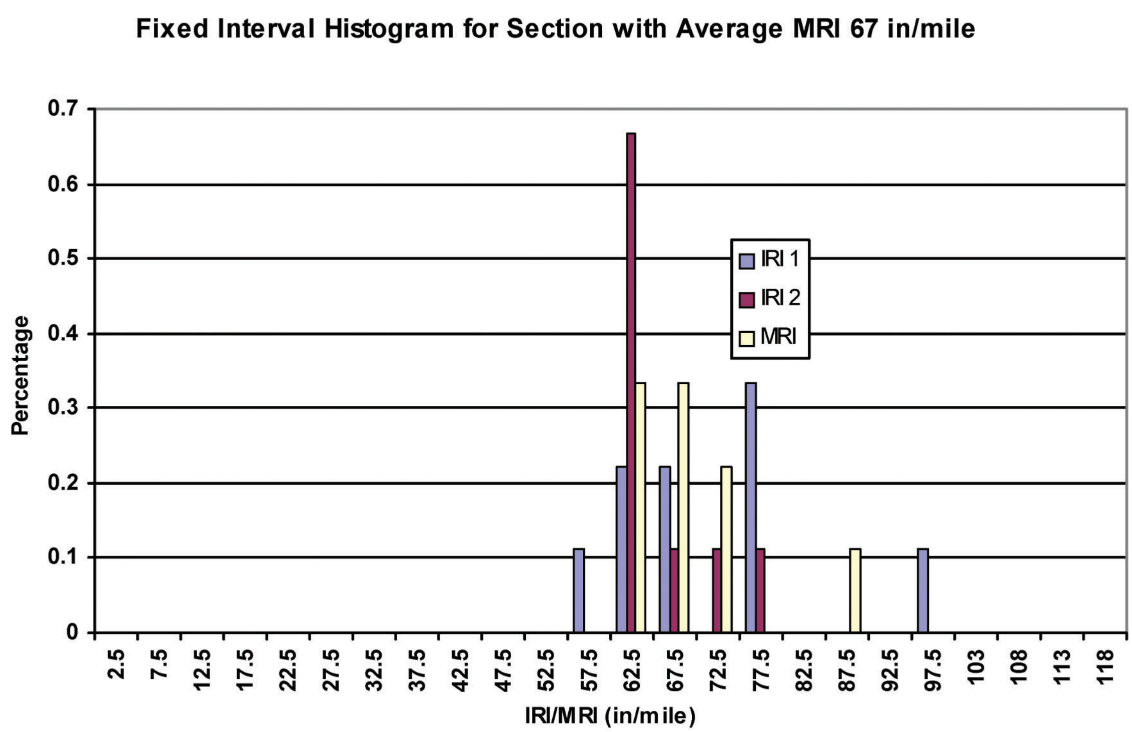

Figure 3.28 Histogram of fixed interval IRI and MRI values for pavement section.

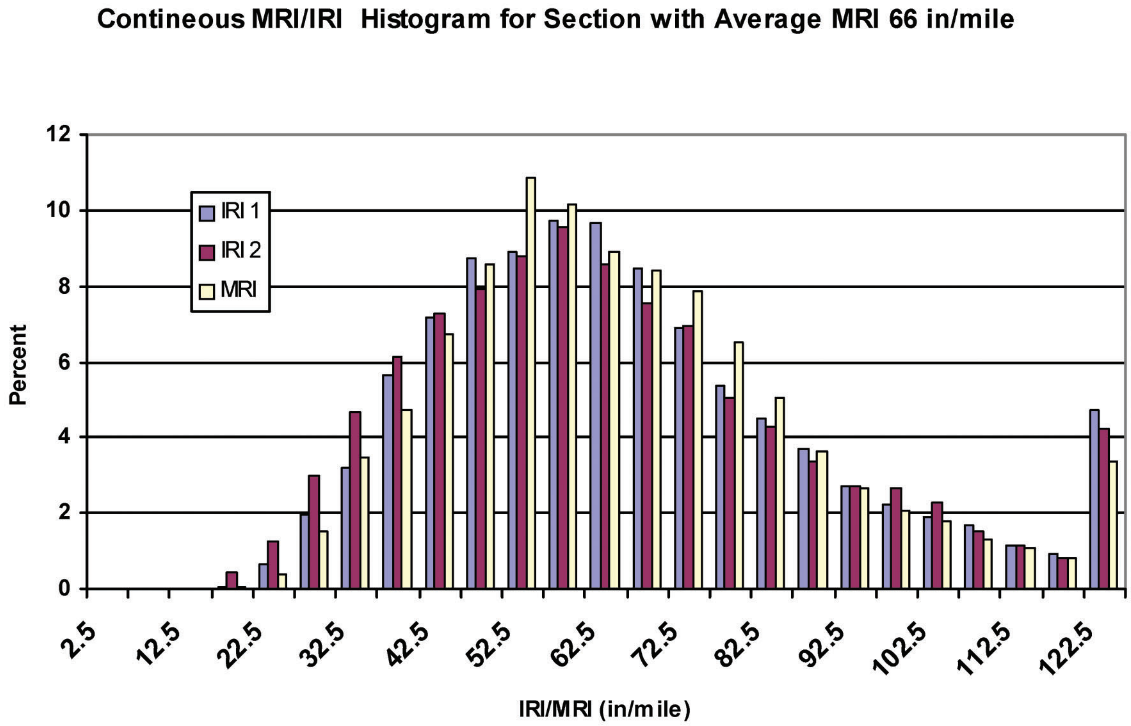

Figure 3.29 Histogram of fixed interval IRI and MRI values for pavement section.

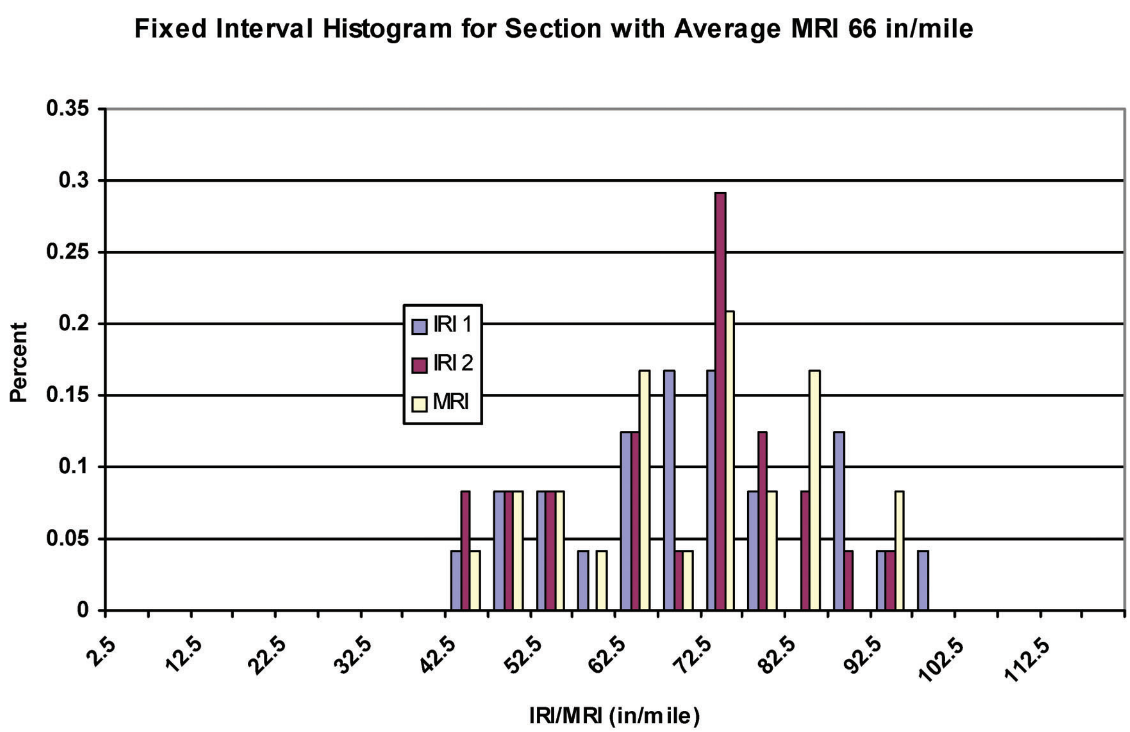

Figure 3.30 Histogram of fixed interval IRI and MRI values for pavement section.

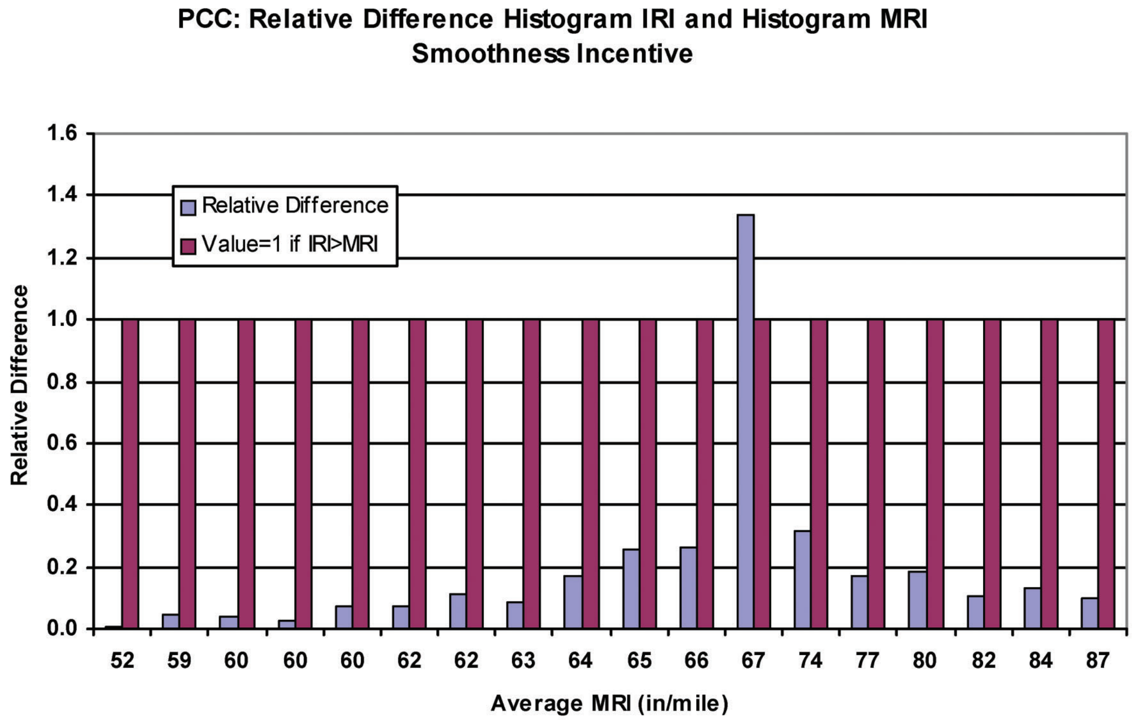

Figure 3.31 PCC continuous: relative difference between IRI and MRI incentives.

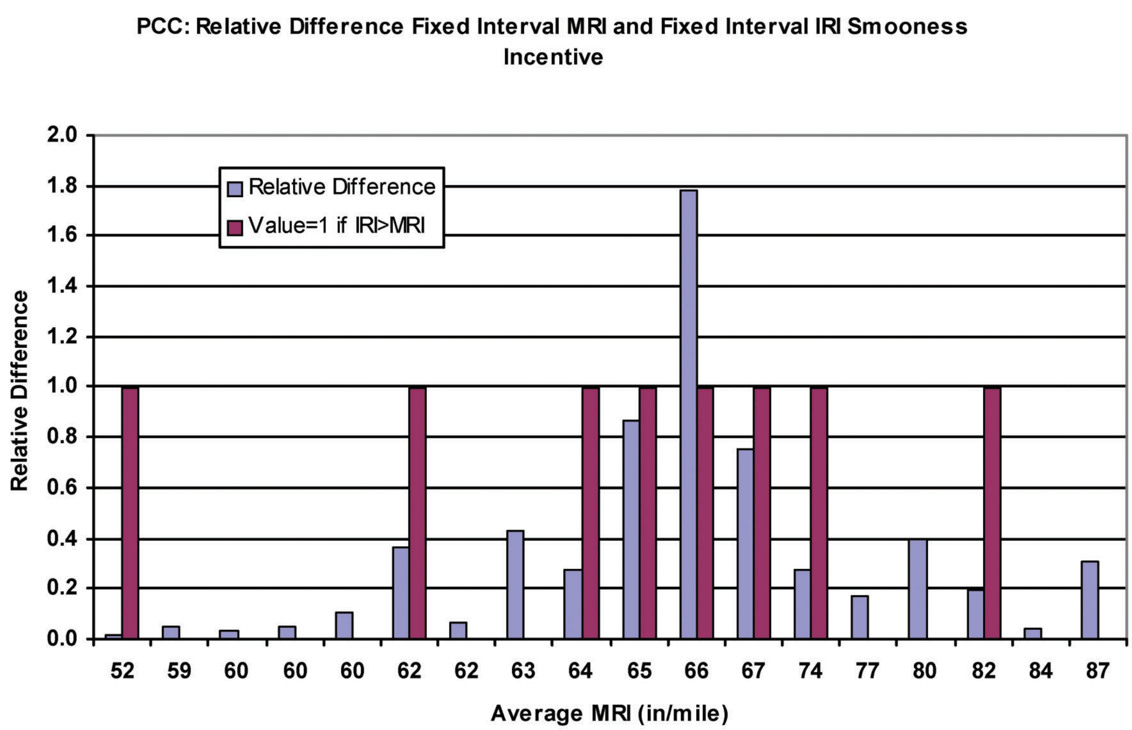

Figure 3.32 PCC interval: relative difference between IRI and MRI incentives.

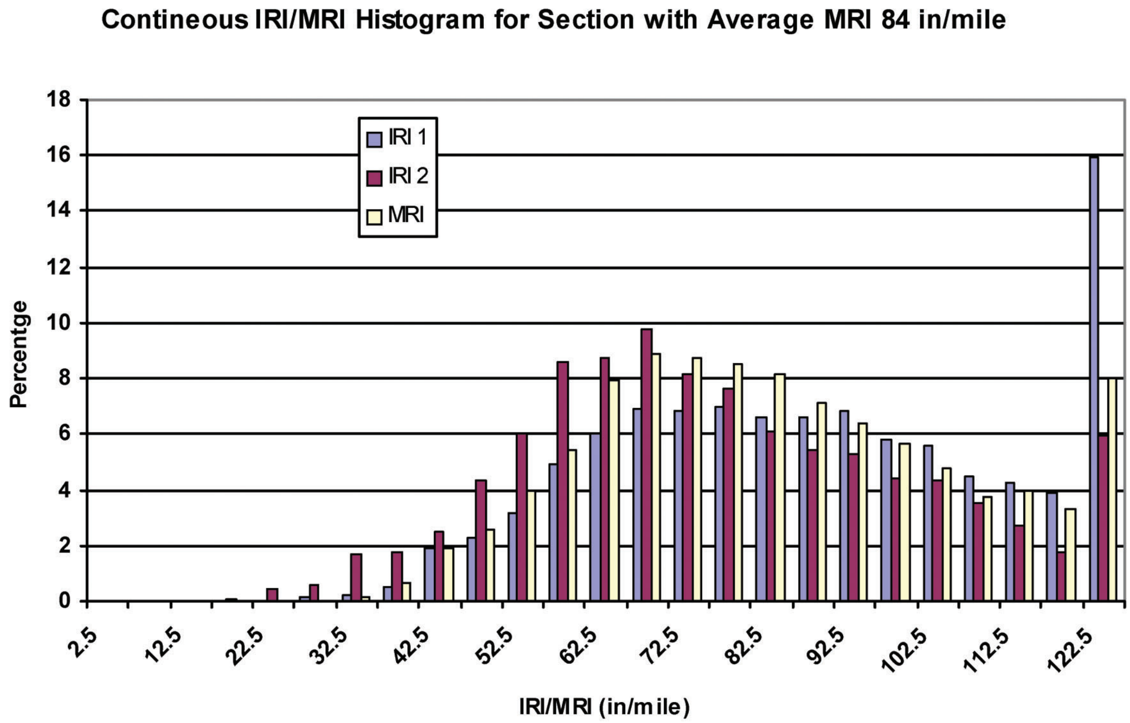

Figure 3.33 Histogram of continuous IRI and MRI values for pavement section.

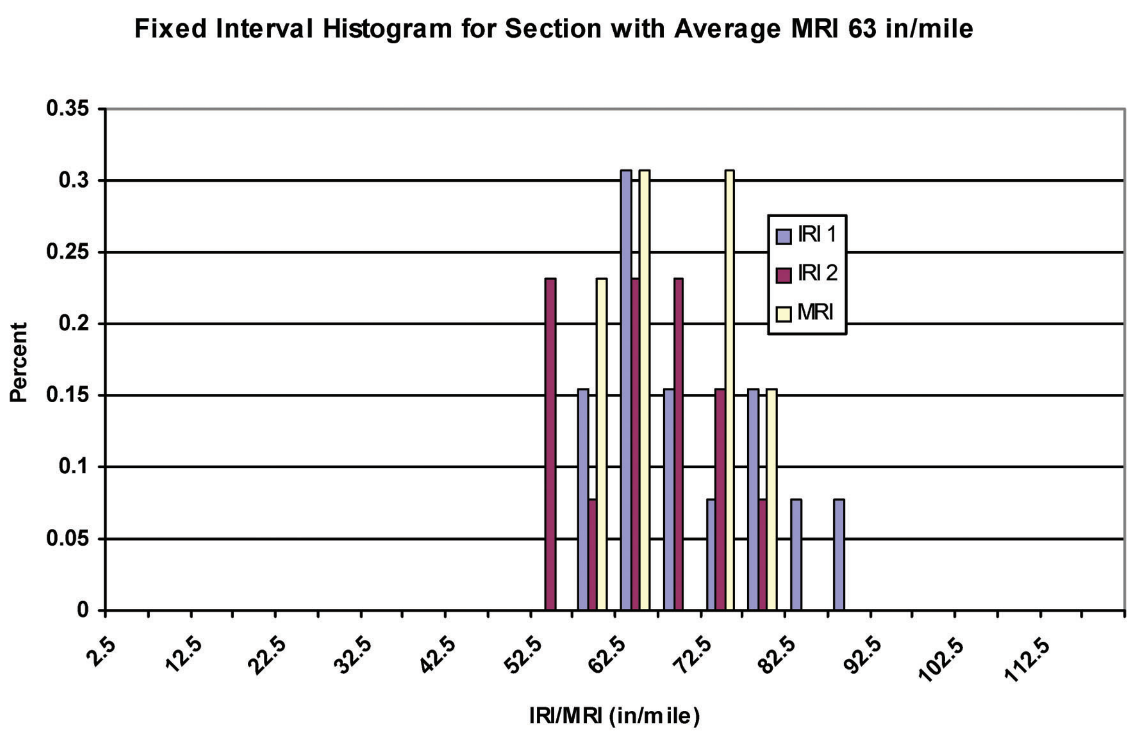

Figure 3.34 Histogram of fixed interval IRI and MRI values for pavement section.

assurance incentives. Utilizing the histogram of the continuous IRI/MRI was selected instead of the fixed interval method for the following reasons:

1. The results of a population analysis demonstrated pavement smoothness values for newly constructed pavements are not normally distributed, but skewed to the right; consequently, there is a notable difference between the mean and the mode for the population. This difference affects the smoothness bonus.
2. A histogram of pavement section provides more true description of the pavement smoothness than the small population of values provided by the fixed interval method, because the fixed interval values are strongly influenced by the characteristics of the lot population positive skew.

Utilizing the IRI values of the individual wheel paths was selected instead of the average MRI for the following reasons:

1. The IRI of the individual wheel path is directly defined by a quarter car model. The average IRI of the two wheel paths (MRI) is not tied directly to a physical model.
2. Utilizing the IRI of the individual wheel path better accounts for smoothness variability between wheel paths. This difference is pronounced for PCC pavements.
3. Utilizing IRI instead of MRI allows a more equitable disincentive when one wheel path is significantly rougher than the other.

4. METHODOLOGY FOR LOCATING AREAS OF LOCALIZED ROUGHNESS

The proposed methodology for locating areas of localized roughness is a six step process utilizing the IRI for each individual wheel path:

1. Location of bumps using continuous IRI with 25 foot widow, threshold 150 in/mile
2. Corrective action to remove bumps
3. Data collection with inertial profiler for verification of corrective action and evaluation for segments with excessive roughness
4. Location of segments with excessive roughness using fixed interval IRI with 100 foot segment. A threshold of 90 in/mile is the proposed threshold.
5. Corrective action to alleviate road segments with excessive IRI
6. Data collection with inertial profiler for verification

A first draft of the language of the specification for locating areas of localized roughness follows:

Smoothness Correction 401.18C

At locations where the inertial profiler is being used on an intermediate course, all areas of localized roughness having deviations, high or low points, with an IRI in excess of 150 in/mile in 25 feet shall be corrected, for each wheel path. After corrective action is taken on an intermediate course, an inertial profiler will be used to verify the adequacy of the corrective action.

If grinding of an intermediate course is used for pavement smoothness corrections, the grinding shall not precede the surface placement by more than 30 calendar days if open to traffic.

At locations where the inertial profiler is being used on a surface course, all areas of localized roughness having deviations, high or low points, with an IRI in excess of 150 in/mile in 25 feet shall be corrected, for each wheel path. After corrective action is taken on a surface course to alleviate the localized roughness, an inertial profiler will be used to verify the adequacy of the corrective action. When the results are acceptable the pavement section will be profiled again. The new profiles of each wheel path will be evaluated for segments with excessive roughness. Any 100 foot section having an IRI greater than 90 inches per mile shall be corrected. After corrective action is taken on the surface course, an inertial profiler will be used to verify the adequacy of the corrective action.

The following are exempted from evaluation for segments with excessive roughness:

- All mainline traveled way lanes shorter than 0.1 mi.
- All mainline traveled lanes within smoothness sections with posted speed limits less than or equal to 45 MPH throughout the entire section length
- All tapers
- All turn lanes, including bi-directional left turn lanes
- All ramps with design speeds of 45 MPH or less
- All acceleration and deceleration lanes associated with ramps with design speeds of 45 MPH or less
- All shoulders

4.1 Bump Location

A review of other mid-western states' current IRI/MRI based specifications revealed that many states locate areas of localized roughness (bumps) using a threshold applied to continuous IRI with a 25 filter window (see Table 4.1). This methodology was selected for utilization as the bump detection methodology for the proposed INDOT specification. The Wisconsin and Ohio Departments of Transportation lobbied for enforcement of a more stringent threshold. The threshold included as part of the INDOT specification is within the bounds of other midwestern states (see Table 4.1).

The 640 miles of pavement sections included in the 2008/2009 HMA population and the 2010 HMA populations respectively, and the approximately 50 miles of pavement sections included in the 2008/2009 and 2010 PCC populations were analyzed for bumps. Results were analyzed for four thresholds 125 in/mile, 150 in/mile, 160 in/mile, and 170 in/mile. The results of the analysis are included in Table 4.2. The number of bumps, linear percentage of bumps, and the width of the bumps increase with a decrease in threshold. The linear percentage is a summation of the bump segments divided by the total length. The average bump width is the average of the section average bump widths. The section average bump width is the average bump width

TABLE 4.1
Bump Location Specifications

State	Current Threshold (in/mile)	Desired Threshold (in/mile)	Description
Indiana (prop)	150		Mandatory Corrective Action Corrected < 150 in/mile
Minnesota	125		Fine Assessed Corrected < 125 in/mile
Ohio	160	150	Mandatory Corrective Action Corrected < 160 in/mile
Wisconsin	175	125	Engineer Determined Corrective Action And/or fine Corrected < 140 in/mile

NOTE: State pavement specifications found at www.smoothpavements.com

for a pavement section. There is a significant decrease in the linear percentage of bumps in the 2010 PCC population verses the 2008/2009 population. The decrease is at least partially due to the fact that 2008/2009 data was collected using dot lasers while the 2010 data was collected using line lasers. For HMA pavement the increase in the linear percentage when the threshold is decreased from 150 to 125 in/mile is 0.95 % which is over twice the increase as when the threshold is dropped from 175 to 125 in/mile, 0.46%. This difference is even more pronounced in the PCC population (see Table 4.2).

4.2 Segments with Excessive IRI

Not all areas localized roughness are limited to or caused by small areas (bumps) of very high IRI values (>150 in/mile); consequently, the draft specification includes a provision to address segments (lots) with excessive IRI. The draft specification defines segments of excessive IRI (bad lots) as 100 foot segments with average IRI values above 90 in/mile.

A study was conducted using two methodologies to define segments of excessive IRI (bad lots). The study included segment lengths of 50 feet, 100 feet, 250 feet, and 528 feet. The first method (Method 1) was to calculate the average IRI of each wheel path for the segment, and flag any segment with an average IRI value above the threshold. The second method (Method 2) was to determine the percentage of points in the segment above the IRI threshold and then flag any segment with a percentage above a set percentage threshold. The IRI thresholds selected for the study included 70, 90, and 125 in/mile. The percentage thresholds selected for method two included 40%, 50%, and 60% of the points. The percentages of the

TABLE 4.2
Bump Location Specifications

Bump Detection Threshold (in/mile)	Number of Bumps	Bump Linear Percentage	Average Distance Between (feet)	Average Bump Width (feet)
		HMA		
125	7,375	2.05%	3,951.18	13.58
150	**4,091**	**1.10%**	**7,454.96**	**11.48**
160	3,291	0.88%	9,413.57	10.90
175	2,486	0.64%	12,000.41	10.03
		2010 PCC		
125	1,002	2.89%	1,047.67	12.66
150	**423**	**1.08%**	**1,985.96**	**9.18**
160	272	0.76%	2,647.47	8.83
175	176	0.47%	3,513.54	7.85
		08/09 PCC		
125	1,879	7.35%	332.03	14.46
150	**891**	**3.20%**	**676.41**	**12.97**
160	660	2.39%	872.47	12.23
175	457	1.57%	1,292.14	11.30

TABLE 4.3
HMA: Percentage of Segments with Excessive IRI

	528 ft Lot	250 ft Lot	100 ft Lot	50 ft Lot
Method 1				
Method 1 Average IRI >70	12%	12%	13%	14%
Method 1 Average IRI >90	4%	4%	5%	6%
Method 1 Average IRI >125	1%	1%	2%	2%
Method 2 Base = 70 (in/mile)				
Threshold 40%	11.49%	12.53%	14.41%	15.95%
Threshold 50%	7.84%	8.90%	11.00%	13.08%
Threshold 60%	5.18%	6.27%	8.36%	10.56%
Method 2 Base = 90 (in/mile)				
Threshold 40%	4.15%	4.77%	6.07%	7.29%
Threshold 50%	2.64%	3.15%	4.40%	5.84%
Threshold 60%	1.60%	2.15%	3.19%	4.54%
Method 2 Base = 125 (in/mile)				
Threshold 40%	0.97%	1.41%	1.99%	2.48%
Threshold 50%	0.59%	0.90%	1.42%	1.93%
Threshold 60%	0.25%	0.55%	1.01%	1.48%

segments with excessive IRI for HMA and PCC included as Table 4.3 and Table 4.4.

The segment size (lot size) of 100 feet was selected as opposed to 528, because, increasing the lot size smoothens the results limiting the overall effect of localized roughness. Changing the lot size from 100 feet to 528 feet would decrease the percentage of segments with excessive IRI from 5% to 4% for HMA and from 10% to 7% for PCC (see Table 4.3 and Table 4.4). The lot size and the IRI threshold directly affect the percentage of segments with excessive IRI. The percentages of lots with excessive IRI (bad lots)

TABLE 4.4
PCC: Percentage of Segments with Excessive IRI

	528 ft Lot	250 ft Lot	100 ft Lot	50 ft Lot
Method 1				
Method 1 Average IRI >70	31%	31%	32%	32%
Method 1 Average IRI >90	7%	9%	10%	12%
Method 1 Average IRI >125	0%	1%	1%	2%
Method 2 Base = 70 (in/mile)				
Threshold 40%	34.88%	36.48%	37.04%	37.23%
Threshold 50%	25.91%	25.63%	28.92%	31.07%
Threshold 60%	17.14%	17.93%	21.80%	25.23%
Method 2 Base = 90 (in/mile)				
Threshold 40%	9.98%	11.00%	13.10%	14.75%
Threshold 50%	4.44%	6.83%	9.11%	11.86%
Threshold 60%	2.12%	3.83%	6.20%	8.76%
Method 2 Base = 125 (in/mile)				
Threshold 40%	0.10%	0.68%	1.62%	3.00%
Threshold 50%	0.10%	0.44%	0.82%	2.14%
Threshold 60%	0.00%	0.24%	0.51%	1.25%

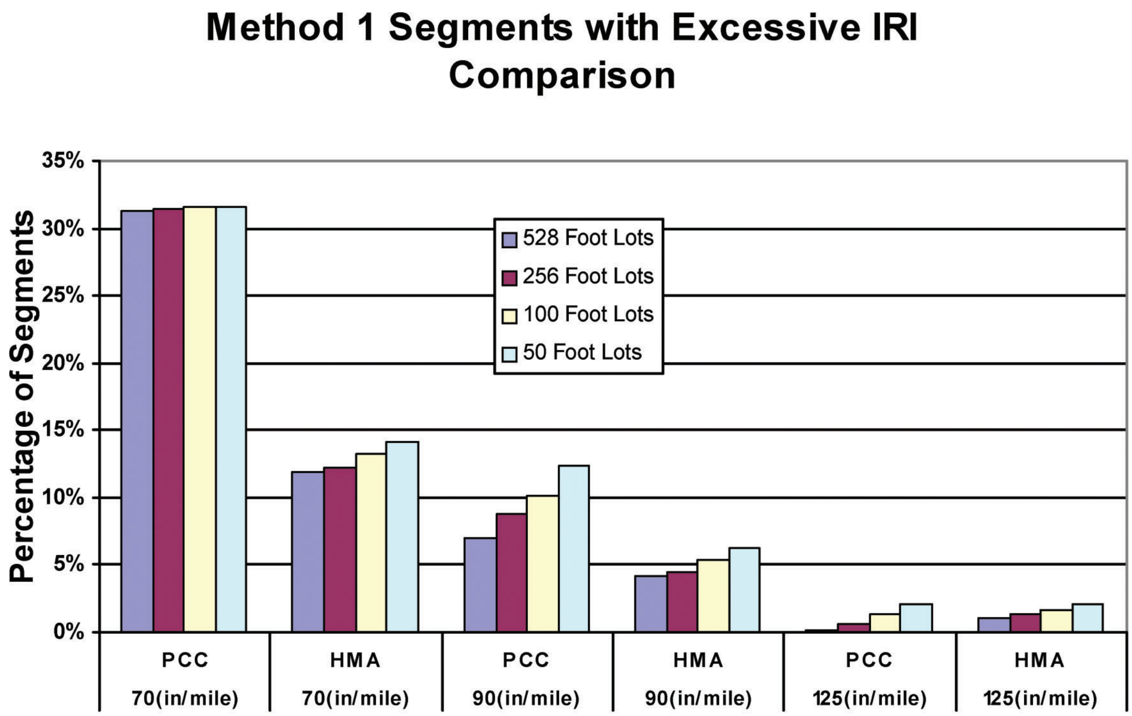

Figure 4.1 Method 1 segments of excessive IRI comparison.

decrease with an increase in segment/lot size and IRI threshold (see Figure 4.1 and Figure 4.2).

Method 1 utilizing the average IRI was selected for the specification for locating segments of excessive IRI (bad lots) because Method 2 cannot be easily implemented utilizing ProVAL. A study was conducted to examine the relationships between the bad lots, and bumps Figure 4.3 and Figure 4.4 describe

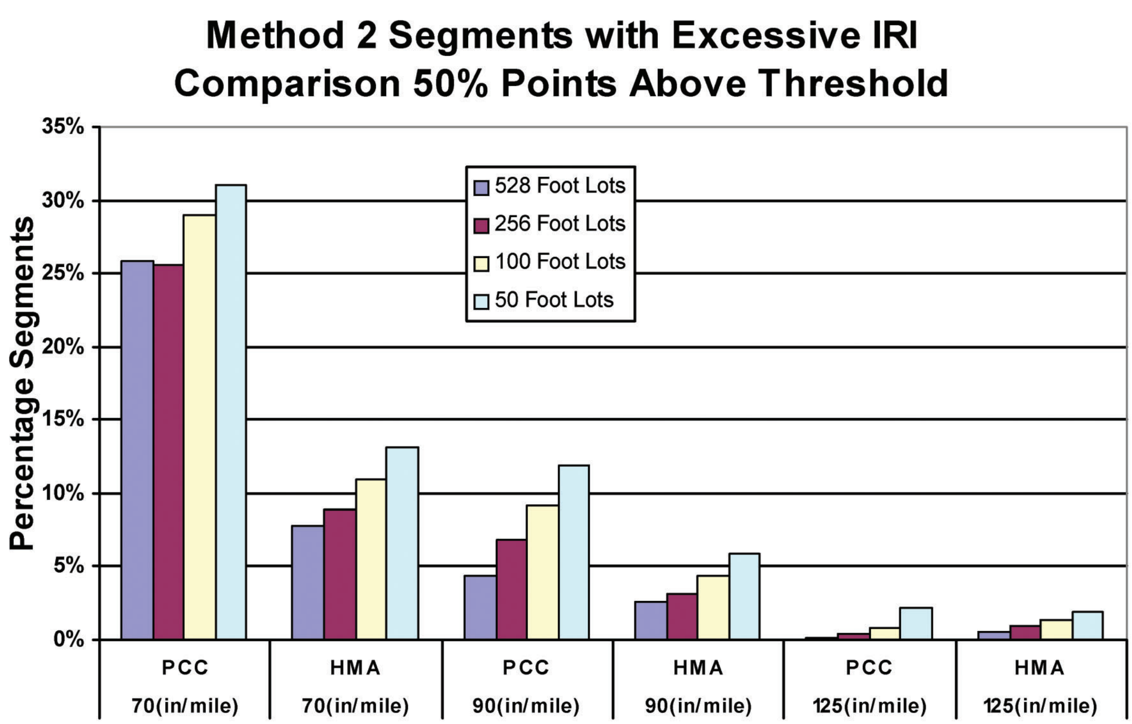

Figure 4.2 Method 2 segments of excessive IRI comparison.

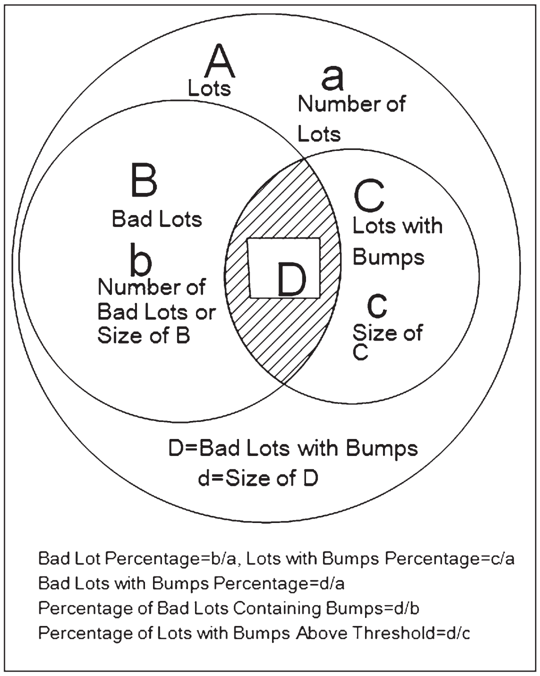

Figure 4.3 Set and subset descriptions bad lots, bumps.

the sets utilized to examine the relationships. As shown in Table 4.5, 5.4 % of the HMA lots are bad, and 6.6% of the PCC lots are bad. For the selected methodology bad lots occur in both wheel paths simultaneously 25% of the time for the HMA

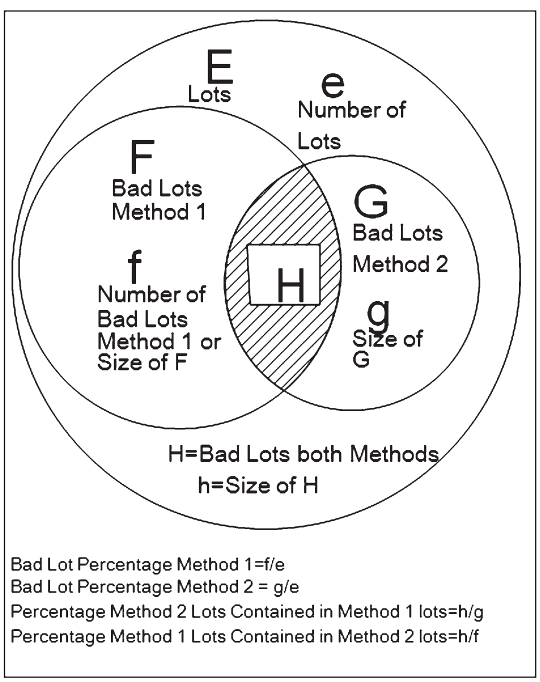

Figure 4.4 Set and subset descriptions bad lots methods 1 and 2.

population and 28% of the time for the PCC population (see Table 4.5). Therefore, corrective action on the whole width of the pavement will fix two bad lots about a quarter to a third of the lots. Furthermore, 65% and 52% of the HMA bad lots and PCC bad lots also contain bumps respectively (see Table 4.5); consequently, more than half of the bad lots could conceivably be corrected during corrective action for bumps. 93% and 90% of the bad lots flagged using Methodology 2 (50% of points above threshold) would be corrected by corrective action on the bad lots for the HMA and PCC populations respectively (see Table 4.5).

4.3 Comparison of Proposed Areas of Localized Roughness Method with Current Method

A comparison between the proposed bump detection method and the current bump detection method was not conducted. In most cases the IRI data was collected after the contractor had opportunity for corrective action; consequently, the inertial profile data was most likely collected after the bumps detected with the PI were corrected. Furthermore, the IRI data was collected after station markings had been removed or knocked down hindering the comparison.

A comparison was made between the number and percentage of segments classified as bad (needing corrective action) utilizing the proposed specification for segments with excessive IRI and the number and percentage of lots classified as bad utilizing the current specification. The current specification includes corrective action for a 528 foot lots with PI indexes above 3.4 inches for HMA, or 3.8 inches for PCC. The proposed specification includes corrective action for 100 foot segments with average IRI values above 90 in/mile. For this comparison, the inertial profile data may have been collected after corrective action for the pavement sections. Table 4.6 contains the results of a comparison of PI index corrective action lots and the proposed IRI segments with excessive IRI for a selection of road sections (see Table 4.6). For the proposed specification, a 100 foot lot is split into two segments one under each wheel path, the current specification utilizes a 528 foot lot. Consequently, there are more than 10 times as many segments evaluated using the proposed specification as opposed to the current specification. The table also includes results utilizing MRI on the 100 foot lots instead of IRI. The lot is not split when MRI is utilized. The results of the comparison show that more lots were classified as bad lots utilizing the proposed specification than with the current specification (see Table 4.6). Table 4.7 contains the results for utilizing a 528 foot lot size for the MRI and IRI classification instead of a 100 foot lot size. Increasing the lot size decreased the percentage of lots classified as bad.

TABLE 4.5
Bad Lot and Bump Set Percentages

	Set	HMA Population		2010 PCC Population	
Lot size		100 ft	528 ft	100 ft	528 ft
Number of lots		79,560	15,158	5,114	992
Lots with bumps percentage		4.6%	13.1%	6.6%	24.2%
Method 1 (Specification Method)					
Bad lot percentage	b/a	5.4%	4.1%	10.2%	7.1%
Left and right lots both bad percentage		25.3%	29.2%	28.3%	18.6%
Percentage of lots that are bad and contain bumps	d/a	3.5%	3.9%	5.3%	6.9%
Percentage of bad lots containing bumps	d/b	65.1%	95.8%	52.3%	97.1%
Percentage of lots with bumps that are also bad	d/c	77.3%	30.0%	80.2%	28.3%
Method 1/Method 2					
Percentage of bad lots Method 2 contained in bad lots Method 1	h/g	93.3%	98.0%	89.7%	93.2%
Percentage of bad lots Method 1 contained in bad lots Method 2	h/f	75.8%	62.9%	80.4%	58.6%

TABLE 4.6
Comparison Table PI and IRI

Road	Type	Lane	IRI Number of Segments	IRI # of Bad	IRI % Bad	PI Number of Segments	PI # of Bad	PI % Bad	MRI # of Bad	MRI % Bad
US 24	PCC	EBD	182	0	0.0%	17	0	0.0%	0	0.0%
US 24	PCC	EBP	182	0	0.0%	17	0	0.0%	0	0.0%
US 231	PCC	NBD	294	5	1.7%	29	0	0.0%	3	2.0%
US 231	PCC	NBP	294	8	2.7%	29	0	0.0%	3	2.0%
US 231	PCC	SBD	294	17	5.8%	29	0	0.0%	7	4.8%
US 231	PCC	SBP	294	11	3.7%	29	0	0.0%	6	4.1%
US 50 S1	HMA	EBD	322	0	0.0%	31	0	0.0%	0	0.0%
US 50 S1	HMA	WBD	322	0	0.0%	31	0	0.0%	0	0.0%
US 50 S2	HMA	EBD	200	0	0.0%	19	0	0.0%	0	0.0%
US 50 S2	HMA	WBD	200	0	0.0%	19	0	0.0%	0	0.0%
US 41 S1	HMA	NBD	200	2	1.0%	20	0	0.0%	1	1.0%
US 41 S1	HMA	NBP	200	2	1.0%	20	0	0.0%	1	1.0%
US 41 S1	HMA	SBD	200	6	3.0%	20	0	0.0%	3	3.0%
US 41 S1	HMA	SBP	200	3	1.5%	20	0	0.0%	2	2.0%
US 41 S2	HMA	NBD	112	7	6.3%	11	0	0.0%	3	5.4%
US 41 S2	HMA	NBD	112	7	6.3%	11	0	0.0%	4	7.1%
US 41 S2	HMA	SBP	112	10	8.9%	11	0	0.0%	4	7.1%
US 41 S2	HMA	SBP	112	8	7.1%	11	0	0.0%	3	5.4%
SR 56	HMA	EBD	212	33	15.6%	20	1	5.0%	8	7.5%
SR 64 S1	HMA	EBD	774	13	1.7%	73	0	0.0%	5	1.3%
SR 64 S1	HMA	WBD	774	53	6.8%	73	1	1.4%	18	4.7%
SR 64 S2	HMA	EDB	280	4	1.4%	29	2	6.9%	2	1.4%
SR 64 S2	HMA	WBD	280	0	0.0%	29	2	6.9%	0	0.0%
SR 29	HMA	NBD	436	4	0.9%	41	1	2.4%	2	0.9%
SR 29	HMA	SBD	416	3	0.7%	40	0	0.0%	2	1.0%
Total HMA			5464	155	2.8%	529	7	1.3%	58	2.1%
Total PCC			1540	41	2.7%	150	0	0.0%	19	2.5%

NOTE: PI specification utilizes 528 ft lots. Proposed IRI specification utilized 100 ft lots. For the Proposed IRI specification the 100 ft lot split into two segments

TABLE 4.7
Comparison Table IRI and MRI 528 ft Lots

Road	Type	Lane	Number of Segments	IRI # of Bad	% Bad	# of Bad	MRI % Bad
US 24	PCC	EBD	34	0	0.0%	0	0.0%
US 24	PCC	EBP	34	0	0.0%	0	0.0%
US 231	PCC	NBD	58	0	0.0%	0	0.0%
US 231	PCC	NBP	58	0	0.0%	0	0.0%
US 231	PCC	SBD	58	1	1.7%	1	3.4%
US 231	PCC	SBP	58	1	1.7%	0	0.0%
US 50 S1	HMA	EBD	62	0	0.0%	0	0.0%
US 50 S1	HMA	WBD	62	0	0.0%	0	0.0%
US 50 S2	HMA	EBD	38	0	0.0%	0	0.0%
US 50 S2	HMA	WBD	38	0	0.0%	0	0.0%
US 41 S1	HMA	NBD	40	0	0.0%	0	0.0%
US 41 S1	HMA	NBP	40	0	0.0%	0	0.0%
US 41 S1	HMA	SBD	40	0	0.0%	0	0.0%
US 41 S1	HMA	SBP	40	0	0.0%	0	0.0%
US 41 S2	HMA	NBD	22	2	9.1%	0	0.0%
US 41 S2	HMA	NBD	22	2	9.1%	1	9.1%
US 41 S2	HMA	SBP	22	2	9.1%	0	0.0%
US 41 S2	HMA	SBP	22	2	9.1%	0	0.0%
SR 56	HMA	EBD	40	3	7.5%	0	0.0%
SR 64 S1	HMA	EBD	146	0	0.0%	0	0.0%
SR 64 S1	HMA	WBD	146	3	2.1%	1	1.4%
SR 64 S2	HMA	EDB	58	0	0.0%	0	0.0%
SR 64 S2	HMA	WBD	58	0	0.0%	0	0.0%
SR 29	HMA	NBD	82	0	0.0%	0	0.0%
SR 29	HMA	SBD	80	0	0.0%	0	0.0%
Total HMA			1058	14	1.3%	2	0.4%
Total PCC			300	2	0.7%	1	0.7%

NOTE: IRI and MRI 528 ft lots. 528 ft lot split into two segments for IRI.

5. VERIFICATION

Quality control/quality assurance is an important consideration for monitoring smoothness of newly constructed pavements. Consequently, INDOT's right to conduct verification testing to validate the quality of the inertial profile data collected and data analysis included as part of pavement smoothness quality assurance should be included as part of the pavement smoothness specification. The proposed INDOT verification testing description is based off the Wisconsin Department of Transportation Ride Incentive IRI Ride specification (Item 440.4410.S.) 1. The verification portion of the proposed specification follows:

- The Department may conduct verification testing (QV) to validate the quality of the product. A certified department profiler technician will perform the QV testing.
- The Department will notify the contractor before testing so the contractor can observe the QV testing. Verification testing will be performed independent of the contractor's QC work using separate equipment from the contractor's QC tests.
- The Department and Contractor will jointly investigate any testing discrepancies. The investigation may include additional testing as well as review and observation of both the Department's and Contractor's testing procedures and equipment. Both parties will document all investigative work.
- If the Contractor does not respond to a Department's request to resolve a testing discrepancy, the Department may suspend production until action is taken.

C.6 Dispute Resolution

- The engineer and contractor should make every effort to avoid conflict. If a dispute between some aspect of the contractor's and engineer's testing program does occur, seek a solution mutually agreeable to the project personnel. The department and contractor may review the data, examine the data reduction and analysis methods, evaluate testing procedures, and perform additional testing.
- If the project personnel cannot resolve a dispute and the dispute affects the payment or could result in incorporating nonconforming pavement, the department will use third party testing to resolve the dispute. The department's Quality Assurance Unit, or a mutually agreed on independent testing company, will provide this testing. The engineer and contractor will abide by the results of the third party tests. The party in error will pay for the service charges incurred for testing by an independent tester. The department may use third party tests to evaluate the quality of questionable pavement and determine the appropriate payment.

6. INERTIAL PROFILER CERTIFICATION

This chapter discusses the procedures for certification of inertial profilers utilized for providing profiles for which newly constructed pavement smoothness is evaluated. The personnel operating the profilers should be certified as well as the inertial profiling equipment. This certification process is an effort to ensure the quality of the smoothness data collected on newly constructed pavements. Inertial profiler certification requires the selection of a site, preparation of the site, and protocol for operator and inertial profiler certification. The proposed INDOT certification procedures are based off a review of current practices in other states especially the most recently revised. This includes the inertial profiler certification process of the Wisconsin Department of Transportation, the Minnesota Department of Transportation 1.

6.1 Certification Site Selection

The following parameters should be considered when evaluating sites for inertial profiler certification.

- The profile of the road segment (the road should be flat)
- The geometry of the road segment (the road should be straight)
- The length of the road segment (the segment should be at least 700 feet long).

- The road condition (the road segment should be in good condition).
- Pavement properties

  - Open graded HMA, dense graded HMA, or SMA are the HMA pavement sections preferred
  - Longitudinal tined PCC pavement preferred

The road profile and geometry are important considerations for inertial profiler certification due the functionality of the inertial profiler. Most if not all inertial profilers use single axis accelerometers to account for vehicle motion. The presence of vertical and or horizontal curves in the road can introduce small errors in the profile which can lead to problems with certification. Utilizing a straight flat road segment for certification eliminates an error source.

The road needs to be long enough to provide a thorough analysis of the system. The proposed specification states that the road segments need to be at least 700 feet in length. The first and last 100 feet of the segment are for acceleration and deceleration respectively leaving at least 500 feet of the segment for evaluation for certification procedures.

The condition of the road affects inertial profiler certification for two reasons. There is higher variability in the roughness in roads in poor condition. This variability can lead to problems with certification. The inertial profilers will be utilized for evaluating newly constructed pavements for the specification; consequently, the profilers should be certified on pavement segments that are in similar condition.

The pavement properties are also an important consideration. Texture variability and tinning affects the precision and the accuracy of profiles collected with inertial profilers. There is increased variability in profiles collected on tinned or dense graded HMA caused by the laser point or line falling in and out of the tines and are textures of the pavement. Furthermore, the profile variability of longitudinal tinned PCC pavement is larger than that for transversely tinned PCC pavements. The certification should be conducted on pavements reflecting the worst case scenario expected to be encountered. Consequently, dense graded HMA pavement and longitudinal tinned PCC should be used for certification if roads are constructed using them.

6.2 Certification Site Preparation

Proper preparation of the certification cite prior to certification improves efficiency and helps ensure the quality control of the certification process. The following steps are a selected set of site needs preparation tasks prior to certification of the inertial profilers.

- Set up the HMA and PCC certification segments

  - Paint parallel lines in each wheel path on the road segments
  - First 100 feet of segment for acceleration
  - At least 500 feet for certification
  - Last 100 feet of segment for deceleration
  - Set up on of the segments for calibration of distance measurement instruments (DMI)

- Collect 3 data runs on each wheel path the reference profiler (SURPRO 3000)
- Verify the repeatability/precision of the reference profiles utilizing the ProVAL software package

The certification process requires that the inertial profiler operator drive the profiler over the same track on the road for multiple passes. Consequently, both wheel paths should be painted the entire length of the test segment to provide a reference for the operators. Furthermore, targets should be placed across the entire width of the road at the start and end of the 500 foot section. This target should provide a large enough elevation difference to be easily identified in inertial profile data.

The certification process requires establishing a reference profile for each of the wheel paths. For the proposed INDOT specification, the reference profiles will be established using the reference profiles purchased for this purpose the SURPRO 3000 walking profiler. Three runs of data will be collected in each wheel path with the reference profiler to establish the repeatability and precision of the reference profiles. The profiler certification module of ProVAL will be used to verify the repeatability/precision of the reference profiles. The cross correlation of the three runs of the reference profiler must be greater than or equal to 95%.

6.3 Inertial Profiler Certification Protocol

The inertial profiler certification protocol includes provisions for insuring the inertial profiling equipment is in calibration, the precision of the inertial profiler is acceptable, the accuracy of the inertial profiler is acceptable and verification of the IRI calculated from the profiles. The following is an outline of the certification process:

- On site inertial profiler calibration

  - DMI calibration
  - Elevation/height calibration
  - Bounce Test

- Data Collection
- Repeatability/Precision Certification
- Accuracy Certification
- Verification of IRI

Prior to certification the operator needs to provide documentation from the equipment manufacturer that the equipment can be classified as a class 1 profiler in accordance with ASTM E950-98. Furthermore, the equipment operator must prove that the system utilizes Line lasers with a footprint of at least 3 inches. Prior to any data collection for inertial profiler certification the equipment must be properly calibrated. This calibration should be done at the certification site. This calibration includes an elevation height calibration done utilizing the equipment manufactures software and procedures; however, the height calibration should include height measurement of a minimum of three blocks with the following heights: 0.25 inches, 0.5 inches, and 1 inch. The elevation needs to be within 0.01 inches of the actual block height. A bounce test needs to be conducted with the equipment to ensure that the accelerometer is functioning properly. The DMI needs to be calibrated and verified. The verification run on the test segment must show that the distance provided by the DMI is within 0.1% of the actual distance.

The INDOT certification of the inertial profilers includes criteria for repeatability/ precision, accuracy, and a verification of IRI values. The INDOT certification procedures in the specification were assembled using other DOT specifications and AASHTO standard R56-10 (see Table 6.1).

The repeatability/precession of the inertial profiler is tested by calculating the cross correlation of all of the profile runs for an individual wheel path with an IRI filter applied. The certification requires the cross correlation values for each of the five runs must be greater than or equal to the selected threshold 92% (see Table 6.1). This cross correlation will be performed using the certification module of the ProVAL software package. The cross correlation threshold selected is the same as the AASHTO standard R56-10 and the Wisconsin Department of Transportation (see Table 6.1).

The accuracy of the inertial profiler is evaluated by calculating the cross correlation of the five runs of the data for the individual wheel paths with reference profile for the wheel path with the IRI filter applied. The certification requires the cross correlation values for each of the five runs with the reference profile must be greater than or equal to the selected threshold 90% (see Table 6.1). This cross correlation will be performed using the certification module of the ProVAL software package. The cross correlation threshold selected is the same as the AASHTO standard R56-10, the Wisconsin Department of Transportation, and the Minnesota Department of Transportation (see Table 6.1).

The IRI values of the inertial profiles will be validated for each of the test sections this will be done by computing the test section average IRI values for each of the five runs and the reference profile. The average IRI value and standard deviation of the 5 run averages will also be computed. For certification, the computed IRI for each run must be within 5% of the reference profile value. Furthermore the computed IRI for each run must be within 5% of the average IRI value, and the standard deviation of the five runs must be less than or equal to 3% of the average IRI of the five passes.

6.4 Inertial Profiler Operator Certification

The certification of the operator is done to ensure the quality of the data collected by the operator; therefore, as part of the certification the operator demonstrates that he or she can successfully complete the tasks necessary for smoothness evaluation of newly constructed pavement including the following:

- Perform Inertial profiler calibration
- Collect inertial profile data on certification section
- Utilize ProVAL to calculate a smoothness quality assurance calculation
- Utilize ProVAL for locating areas of localized roughness
  - Locate bumps
  - Locate segments of excessive roughness
- Properly fill out all pertinent paperwork and logs

Proper training of the inertial profiler operators is important; consequently, mandating completion of some form of yearly training should be considered as part of the certification process. The Minnesota

TABLE 6.1
Certification Parameters

Agency	# of Runs	Repeatability: Precision Cross Correlation	Repeatability: Accuracy Cross Correlation	IRI Verification
INDOT Proposed	5	92%	90%	Run IRI ≤ 5% when compared with the reference Run IRI ≤ 5% of the average IRI of the runs STD ≤ 3% of the average IRI of the runs
WISDOT	5	92%	90%	NONE
AASHTO	10	92%	90%	Run IRI ≤ 2% when compared with the reference
MNDOT*	5	85%	90%	Average of runs ≤ 5% when compared with reference STD ≤ 3% of the average IRI of the runs
ODOT	5	NA	NA	Run IRI ≤ 5% of the average IRI of the runs Average IRI ≤ 7% or 5 in/mile when compared with the reference

NOTE: State pavement specifications found at www.smoothpavements.com.
*For MNDOT the average cross correlation of the 5 runs must be at least 90%

Department of Transportation requires completion of online training as for operator certification.

7. INERTIAL PROFILER TRAINING

Training is an important facet of converting from the current smoothness specification and the implementation of the new pavement smoothness specification. The training should include INDOT personnel as well as the road construction contractors. The result of a proper training program is improvement in the quality of the pavement smoothness program and the smoothness of newly constructed pavements in the state of Indiana.

As part of implementing the new smoothness specification INDOT should develop instructions for collecting inertial profile data collection and instructions for submitting pavement smoothness measurement results including instructions on utilizing ProVAL for this process. These documents could be included as training materials hosted on the INDOT website. Both the Minnesota Department of Transportation and the Wisconsin Department of Transportation include online training as part of their pavement smoothness websites.

The construction of smoother roads is the benefit from investing in contractor education. The utilization of inertial profilers prior to bidding allows the contractor to factor the initial pavement smoothness into the prediction of the smoothness assurance adjustment (smoothness bonus). Furthermore, utilizing inertial profilers for quality control during construction allows adjustments and fixes to be made to ensure construction of a smooth pavement, thus maximizing the smoothness assurance adjustment.

Some examples of training materials from other DOT's can be found at the following URLs:

- Minnesota Department of Transportation Training

  http://www.dot.state.mn.us/materials/smoothnesspubs.html

- Ohio Department of Transportation Supplemental Instructions

  http://www.dot.state.oh.us/Divisions/Planning/TechServ/prod_services/Documents/Infrastructure/RideQuality/1110_04182008_for_2008.pdf

- Wisconsin Department of Transportation ProVAL training

  http://roadwaystandards.dot.wi.gov/standards/qmp/

8. CONCLUSIONS

This report presents an inertial profiler IRI based smoothness specification for newly constructed pavements. The process developing a draft specification included developing pay factor tables, developing the methodology for calculating the smoothness bonus, developing methodology for locating areas of localized roughness, and developing inertial profiler certification procedures.

8.1 Conclusions: Pay Factor Table Development

The pay factor tables developed for this study used a linear model that utilized an IRI life cycle model and LCCA. The study demonstrated that a multitude of very different pay factor tables could be generated with this modeling scheme using reasonable model inputs. The pay factor table values were very sensitive to the pavement rehabilitation plan. Furthermore the pay factor table values proved sensitive to the AADT, IRI threshold, and the duration of the LCCA analysis.

The proposed pay factor tables yield smoothness bonus values comparable to bonuses determined using the current specifications.

8.2 Conclusions: Population Analysis

The population study showed that the MRI populations are not normally distributed, but are skewed to the right. The right tail of the MRI populations reflects the smoothness irregularities present in the pavement. These smoothness irregularities (tail) have a pronounced impact on the fixed interval and continuous MRI populations and the calculated smoothness incentives. The positive skew characteristics were also present in the smaller MRI populations utilized for calculating the fixed interval MRI.

More than 82% of the 2010 HMA continuous MRI population is eligible for a smoothness incentive, and more the 55% of the population qualified for the biggest pay factor (1.06). These numbers decrease to more than 79% and 48% respectively for the 2010 HMA fixed interval populations. Less than 39% of the 2010 PCC continuous MRI population qualified for a smoothness incentive, while less than 5% qualified for the biggest pay factor. These numbers decrease to less than 28% and 1% respectively for the 2010 PCC fixed interval populations.

The percentage of the HMA populations that qualify for the biggest pay factor (1.06) is large; however, the calculated incentive was reasonably close to incentives calculated using the current specification for many pavement sections.

Only 67.3% of PCC continuous MRI population met the100% smoothness pay criteria compared 93.15% of the HMA continuous MRI population. There were instances where the proposed specification paid out much more than the current specification and cases where the proposed specification paid out much less.

8.3 Conclusions: Smoothness Assurance Calculation

The proposed smoothness specification utilizes the continuous IRI smoothness histograms of the individual wheel paths to calculate the smoothness quality assurance incentives. Utilizing the histogram of the continuous IRI/MRI was selected instead of the fixed interval method for the following reasons:

1. The results of a population analysis demonstrated pavement smoothness values for newly constructed pavements are not normally distributed.
2. A histogram of pavement section provides more true description of the pavement smoothness than the small population of values provided by the fixed interval method, because the fixed interval values are strongly influenced by the skew characteristics of the individual lot populations.

Utilizing the IRI values of the individual wheel paths was selected instead of the average MRI for the following reasons:

1. The IRI of the individual wheel path is directly defined by a quarter car model. The average IRI of the two wheel paths (MRI) is not tied directly to a physical model.
2. Utilizing IRI instead of MRI allows a more equitable disincentive when one wheel path is significantly rougher than the other.

8.4 Conclusions: Methodology for Locating Areas of Localized Roughness

A two-stage process was selected for locating areas of localized roughness for the proposed specification. The first stage, bump detection, utilizes a threshold of the continuous IRI with a 25 foot window to locate bumps. The second stage, locating segments with excessive IRI, utilizes a threshold of the 100 foot fixed interval IRI values to locate rough road segments.

For the populations examined, bumps accounted for about 1.1% and 1.08% of the length of the HMA and PCC pavement sections respectively.

For the populations examined, 5% and 10% of the HMA and PCC lots respectively were classified as rough (bad). Rough road segments occur in both wheel paths simultaneously about ¼ of the time. Furthermore, 65% and 52% of the HMA rough lots and the PCC rough lots contain bumps respectively; consequently, greater than ½ of the rough lots could conceivably be corrected during bump removal corrective action.

8.5 Conclusions: Certification

The proposed certification procedure includes certification of both the inertial profiler and the profiler operator. The inertial profiler certification includes criteria for repeatability/precision, accuracy, and verification of IRI values. In order to be certified the operator must demonstrate he or she can successfully complete all of the tasks necessary for the smoothness evaluation of a newly constructed pavement.

8.6 Conclusions: Verification and Training

Quality control/quality assurance is an important consideration for monitoring smoothness of newly constructed pavements. Consequently, INDOT's right to conduct verification testing to validate the quality of the inertial profile data collected and data analysis included as part of pavement smoothness quality assurance should be included as part of the pavement smoothness specification.

Training is an important facet of converting from the current smoothness specification and the implementation of the new pavement smoothness specification. The training should include INDOT personnel as well as the road construction contractors. The result of a proper training program is improvement in the quality of the pavement smoothness program and the smoothness of newly constructed pavements in the state of Indiana.

8.7 Future Work

The end result of this study was a draft specification. As with all research, this study exposed questions that were not addressed in the study. Some of these questions follow:

Should the HMA specification be more stringent on multi lift pavements, because the contractor has multiple chances to improve the smoothness of the end product? Some DOT's including WISDOT have a more stringent specification for multi lift HMA pavements.

Should INDOT eliminate or enforce a ceiling on smoothness assurance bonuses paid on thin overlays? After all, currently there are many cases where INDOT pays smoothness bonuses thin overlays that rapidly increase in roughness. How much is INDOT or the departments' customers benefiting from the bonus paid out? The proposed specification does allow for ceilings to be easily emplaced.

Should the correction of areas of localized roughness including bumps and segments with excessive IRI be mandated? The draft specification mandates correction of areas of localized roughness. The Ohio Department of Transportation mandates correction while WISDOT give the project engineer latitude regarding corrective action.

Should INDOT enforce utilizing the ProVAL grinding simulator to estimate smoothness improvement prior to allowing grinding to mitigate areas of localized roughness? The MNDOT smoothness specification includes language limiting the use of grinding based on ProVAL grinding simulation results.

8.8 Implementation of the Draft Specification

The implementation of this draft specification will introduce a method of measuring the road smoothness and a new smoothness index that are much more correlated to user response than the method INDOT currently utilizes for measuring pavement smoothness. Furthermore, implementation of this new specification will ensure that pavement smoothness is measured the same from cradle to grave allowing continuity for tracking of pavement smoothness changes over the life of the pavement. The following tasks need to be addressed for implementation of the draft specification:

1. The draft smoothness specification needs to be written (codified in the design manual)
2. This draft specification needs to be approved by the specification committee.
3. Training materials need to be developed
   a. Inertial profiler operation instructions need to be prepared.
   b. Training presentations for INDOT and contractors need to be developed.
   c. Possibly develop online training
4. INDOT must decide if the smoothness quality assurance testing will be conducted by INDOT personnel.
   a. Purchase of one inertial profiler for each district if INDOT decides to do the smoothness assurance testing.
5. Road segments need to be selected for profiler certification
6. INDOT and or contractor inertial profiler and inertial profiler operators should be certified.

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